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WALKABILITY IN DUBAI: IMPROVING THERMAL COMFORT

Dissertation in partial fulfilment for the
requirements for the degree of

Doctor of Philosophy (Ph.D.)

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London, UK

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ABSTRACT

WALKABILITY IN DUBAI: IMPROVING THERMAL COMFORT

In Dubai, the absurd dependence on air-conditioning in buildings and vehicles has led to sedentary lifestyles and a poor public realm in many outdoor spaces. The microclimatic conditions that have been impaired by the morphology of the built environment, reduced pedestrian comfort between buildings. Urban spaces depreciate for many months due to lack of pedestrians. The present thesis aimed to encourage what it calls walkability – the ability of a place to welcome people to walk– for longer periods every year. It focused on improving pedestrians’ overall thermal comfort and extending the distances that they could travel along their daily utilitarian journeys.

Three main methods of fieldwork were applied to investigate the physical urban environment in two districts, namely Jumeirah Lakes Towers (JLT) and The Greens. First, interviews were conducted with random passers-by along their everyday routes to the mosque, metro, office and school. These were conducted at different periods of the year and times of the day and were meant to identify the thermal comfort limits at such periods. Second, subjective assessments, consisting of thermal sensations and thermal comfort votes, were collected from six subjects over several days in the form of short walks at different times of the year. These helped to assess the influence of the successive changes endured on the thermal sensations and overall comfort. Third, data loggers were installed in four different spaces over a period of one year to identify the influence of urban morphology on the microclimatic parameters (air and globe temperatures and relative humidity). Finally, ENVI-met microclimatic simulations were run to analyse the urban district JLT and identify the hot spots likely to inhibit comfort.

The findings of the fieldwork and simulation studies revealed the prospect for extending the distances that pedestrians tolerate walking outdoors, through improving their thermal sensation and comfort at certain areas along the journey described as the *recovery conditions*. The thesis proposes that allocating adequate shade and wind at frequent areas along the journey provides a psychological satisfaction and physical heat stress relief, which improves the overall comfort and encourages walkability. Proposed scenarios for such areas were modelled and tested using ENVI-met to show the improvements of the microclimate and comfort conditions that can be achieved at different times of the day and year.

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LIST OF ACRONYMS

AH	absolute humidity
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
ASV	Actual Sensation Vote
clo	clothing
CIBSE	Chartered Institution of Building Services Engineers
°C	degrees Celsius
D.B.T.	dry bulb temperature
KLIMES	Project 'Development of strategies to mitigate enhanced heat stress in urban quarters due to regional climate change in Central Europe'
K	Kelvin
Wh/m ²	watt hour per meter square
MAS	Multi-Agent simulations
mPET	Modified Physiological Equivalent Temperature
MRT	mean radiant temperature
m/s	meter per second
m ²	meter square
NCMS	National Centre for Meteorology and Seismology
PLEA	Passive and Low Energy Architecture
PMV	Predicted Mean Vote
PET	Physiological Equivalent Temperature
RH	relative humidity
RUROS	Rediscovering the Urban Realm and Open Spaces
SED	Sustainable Environmental Design
SET	Standard Effective Temperature
SVF	sky view factor
Ta	air temperature

Tcore	core temperature
TCV	thermal comfort vote
Tsk	skin temperature
TSV	thermal sensation vote
V	wind speed

INTRODUCTION

Walkability

"If you plan cities for cars and traffic, you get cars and traffic. If you plan for people and places, you get people and places."

Fred Kent, Project for Public Spaces (Kent, 2005)

Cities are becoming more hospitable to cars than they are to pedestrians. To serve the pace of modern life, large scale streets are expanding indisputably to prevent traffic congestion and accommodate more cars. These new streets drag us into generating the car-oriented cities that we are now getting used to, instead of trying to design streets that favours pedestrian's safety and comfort. Not only because the presence of pedestrians is vital to the liveability of cities. Towns and districts where people walk are significantly more attractive, pleasant and rated as conducive environments. But also, because walkability has a significant role in reducing the carbon matters, which has become one of the world's main concerns. Therefore, as more than half the world's population are living in cities, it is essential for planners to create environments that encourage walkability, by creating pleasant spaces that attract people, which, in turn, generates more conducive environments for other facilities.

The term 'walkability' can be defined as the level of friendliness that the built environment offers to pedestrians (Abley, 2005). Features such as comfort, safety, connectivity and visual attractiveness needs to be provided in friendly environments that intends to support and encourage walking (Southworth, 2005). To make this possible, compact, connected urban environments reduce the distances required to travel between various destinations, which facilitates walking as a means of transport (Azmi et al., 2013). As it satisfies the need for transport on the smallest scale; this scale enables pedestrians to move about flexibly and adaptably (Vasilikou and Nikolopoulou, 2014).

During Dubai's rapid urbanization, this notion has been undermined by the desire to formulate a consumable image of a prodigy city state for the twenty-first century (Kanna, 2013). This has produced an environment that ignores the heritage, essence and traditions of its former urban areas, *Bastakiya* and *Bur Dubai* (see Figure 1). Overseas firms have focused on construction and urban development at speed, creating new luxury communities and iconic structures that form a loose urban fabric (Thapar and Yannas, 2008), such as those in *Jumeirah Beach Residence JBR* and in *Mirdiff* (see Figure 2). The design of the high-energy consuming structures has changed the heat balance under the urban canopy, increasing urban warming. The open spaces with landscape features meant solely for beautification are remarkable, but the microclimate has deteriorated due to unfavourable urban planning and challenging climatic conditions, influencing walkability in many urban areas for a prolonged period every year. Accordingly, the streets have become less pleasant for walkers, due to the lack of solar control and wind flow.



Figure 1 Images of two old districts in Dubai, *Bastakiya* (Left) and *Bur Dubai* (right)
Source: www.2008-2015flashydubai.com

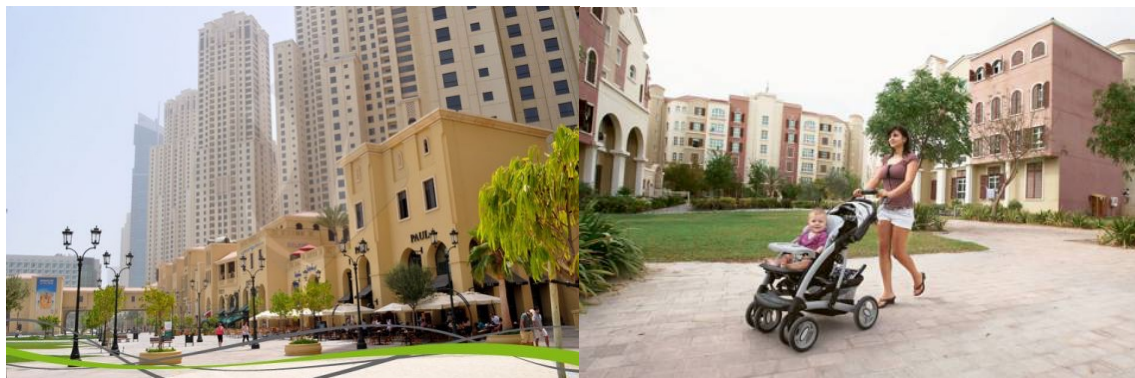


Figure 2 Image of two new districts in Dubai, Jumeirah Beach Residence JBR (left) and Mirdiff (right)
Source: www.visitdubai.com

Town areas are formulated as districts of intense physical nodes – islands with almost no connecting tissue. Concentrated zones of activity, usually in the form of private, clearly bounded, and themed developments, have emerged, leaving the spaces between them to be filled with a low-rise combination of residential villas, desert roads, and small commercial activities (Kanna, 2013). No measures have been taken to provide adequate pedestrian connection between such developments, where the distances involved tend to be measured by the time a car needs to cover them. It is remarkable – but undeniable – that the built environment has been designed for vehicles rather than for pedestrians (Pacione, 2005). In addition, the depreciation of the microclimate has affected the comfort of pedestrians who were encouraged to walk within the boundaries of these developments. The usability of the intervening spaces has been jeopardized and walkability has become conditional on the state of the microclimate and the annual weather. Each swathe of development has its own internal logic, environmental character and patterns of walkability (Kanna, 2013).

Accordingly, sedentary lifestyles and heavy dependence on air-conditioning have evolved (Yannas, 2008; Thapar and Yannas, 2008). Constant exposure to air-conditioned spaces has been shown to make their occupants expect the constant thermal conditions that are typical of mechanical environmental control (Brager and de Dear, 2001), thus discouraging excursions outdoors. Besides, the wide contrast of temperatures between indoors and outdoors (which can exceed 20°C) creates a thermal shock when pedestrians venture outdoors. At certain times of year, the unpleasant experiences of pedestrians who decide to walk affect their presence and patterns in many urban districts for the rest of the year. The distances travelled vary from one area to another, depending on the amount of shade and wind breeze between the routes linking facilities.

Walking patterns are commonly limited to certain months (December, January, February and March) when the climate is pleasant and there is no need of protection from sunlight or heat. During these months, the city's outdoor activities are generally revived with intensified outdoor pursuits. As the weather gets slightly warmer, trips between the outdoor destinations diminish significantly, even when conditions are not particularly bad, and it would be valid to set about improving thermal comfort. Such trips are almost discontinued between June and September, the hottest months of the year. The few pedestrians who venture outdoors during these months seem desperate to protect themselves from the sun and reduce the distances travelled. However, this reveals that pedestrians can be noticeably tolerant of heat, on account perhaps of psychological adaptive measures such as expectation.

The inadequate current practice in urban districts – from the standpoint of material selection, outdoor greening, space morphology and solar control measures – implies a lack of knowledge of pedestrians' comfort limits and of the requirements for local methods of climatic conditioning. Outdoor provision to enhance solar protection without impairing wind flow is needed, but few studies have investigated the climate in Dubai or anything similar. The urban microclimate and thermal comfort in open spaces should play a primary role in urban design and planning (Krüger et al., 2011). Alongside the prevailing concern to generate healthy cities, pedestrians' comfort has become a matter of interest for many researchers. Understanding outdoor microclimates and the way that they influence people's behaviour, existence, and perception of comfort, is a key to successful downtown planning (Chen and Ng, 2011).

Pedestrians' comfort

It is well known that local microclimates formulated by the attributes of the built environment influence people's perception of and satisfaction with their outdoor environment. Pedestrians' behaviours, walking patterns, their frequentation and preferences, depend largely on the urban

setting, its attractiveness and other environmental factors. Individuals prefer to walk in places where other people walk, and activities can be watched, which look beautiful and feel, whether explicitly or implicitly, thermally acceptable. These aspects form the thermal, visual and acoustic conditions which formulate their experience and perception of comfort, hence the time they spend outdoors and their choice for free movement (Vasilikou and Nikolopoulou, 2014).

Walking is considered a multisensory experience, where our perception of the whole environment is certainly affected by any change in the features within (Vasilikou and Nikolopoulou, 2014; Fitch, 1970). Therefore, in harsh climates, the thermal environment of outdoor spaces significantly undermines inhabitants' use of them (Zhang, 2003). This is seen in many urban communities in Dubai, where walkability is seriously impaired by these factors; the lack of solar protection is an obstacle to walking comfortably. The challenging natural climatic conditions are exacerbated by the unfriendliness of the built environment and its anthropogenic heat sources.

Numerous factors determine the levels of pedestrians' satisfaction with their surroundings, such as the environmental conditions, formed by the physical attributes of the spaces and influenced by many psychological parameters (Nikolopoulou et al., 2001). This research focuses mainly on the environmental aspects of comfort, which can be determinant in improving a pedestrians' experience. Very little research has been done on predicting the thermal comfort of a space in relation to preceding spaces. Similarly, few studies have suggested that pedestrians' thermal comfort in any space is significantly influenced by the antecedent space (Chun and Tamura, 2005; Potvin, 2000). It has been accepted that the temperature difference between two sequential spaces, known as the thermal distance, causes thermoregulatory changes, which reduce adaptability. Chen et al. (2011) suggest that the temperature difference between two spaces should be kept at 4°C or less to avoid an overshoot in thermal sensation (Nakano, 2003; Potvin, 2000).

In Dubai, experiencing significant 'steps' or changes in outdoor temperature is a common occurrence where air-conditioned buildings are ubiquitous. Pedestrians suffer a thermal shock as they leave any building, due to the wide difference between temperatures indoors and outdoors (Yannas, 2008). And as they walk along the mixed sequences of sun and shade, they feel a wide temperature difference between the shaded and non-shaded spaces due to large amount of radiations absorbed. These gaps in temperature and the rate of change in the environmental conditions between the outdoor spaces influence thermal comfort dramatically. Potvin, (2000) suggests that, to avoid discomfort and make walking an attractive option, the changes in people's thermal environment along a given path should be small enough to be subliminal. The human body tends to adapt to successive slow changes.

Makaremi et al. (2012) argues that people need some time in a space to adapt to the environmental conditions. Their study, conducted in an educational campus in Malaysia, reveals that individuals who passed through the area for a short time had a low tolerance of uncomfortable thermal conditions, compared to those who came to sit down or relax for a longer period, who had a high tolerance. This evidence gives some idea of how pedestrians struggle to cope with the thermal fluctuations within their environment.

It is also important to differentiate between pedestrians' comfort in a particular space – and at a particular moment – and their overall comfort on a given journey. For instance, pedestrians who are satisfied with their overall journey can still describe themselves as 'very uncomfortable' if interviewed in a warm space. It has been observed, however, that most studies that investigate pedestrians' thermal comfort focus either on the relationship between two sequential spaces or on a particular space. Therefore, a pilot survey was conducted in the present study to identify the more influential factors in people's decision to walk; it was found to be the overall thermal comfort of the journey. Yet, where pedestrians could have taken one of several routes, this was considered subjective. The surveys concluded that pedestrians' perception of their immediate surroundings – variations of sun, shade and wind, etc. – is greatly affected by the microclimate. Finding ways to improve the thermal comfort levels would encourage more people to walk outdoors, extending the walkability patterns.

Aims and objectives

Because the influence of the built environment on pedestrians' thermal comfort, especially in this region, remains under-researched, it is very challenging for urban planners and designers to improve towns and cities by outdoor settings that would foster walkability. The various gaps in knowledge trigger the need for the present report: first, there is a lack of extensive research on outdoor thermal comfort assessments in hot climates, research that investigates people's subjective behaviours and how they are influenced by the microclimate. The findings of large scale environmental investigations, such as KLIMES (Huttner et al., 2009) and RUROS (Nikolopoulou and Lykoudis, 2006), involving subjects from European cities who live in temperate and cold climates, cannot be generalized to the Middle East without calibration. Second, very little attention has been given to the activity of walking, particularly in research on thermal comfort outdoors. Third, there is a lack of instrumentation and indices to measure dynamic thermal comfort. Such gaps of knowledge were noted by Vasilikou and Nikolopoulou (2014). One of the main gaps is of studies that consider from a holistic perspective the impact of the built environment on pedestrians' thermal comfort.

This research investigated pedestrians' thermal comfort in many outdoor spaces in the course of utilitarian daily trips between such facilities as work, metro, school, the mosque, etc. It focuses on the

influence on pedestrians' overall thermal comfort of the thermal transitions between sequential spaces and identifies the troublesome areas in their range of thermal sensations and the possibility of remedying them. The thesis argues that if the physical attributes of the sequential spaces were managed sensibly and efficiently, people could bear to walk for more months in the year. The main goal here is to encourage walkability and connect walkers with varied destinations, reducing their absurd dependency on vehicles. This research aims to improve pedestrians' thermal comfort levels and extend the distances travelled along daily utilitarian routes. The research attempts to answer the questions below:

- How do the different spatial attributes influence the microclimatic conditions and how do they affect pedestrians' comfort levels throughout the year?
- What are the limits of thermal comfort (tolerable conditions) for pedestrians in Dubai? And does the presence of wind extend such limits?
- Can the Physiological Equivalent Temperature (PET) universal index be used to predict thermal comfort in outdoor spaces in this climate?
- How do thermal transitions along pedestrians' journeys (air-conditioned, sunny and shaded spaces) influence their thermal sensation and overall thermal comfort? Does reducing the thermal distance between indoors and outdoors that is endured at the start of the journey, extend the distances that pedestrians are willing to travel?
- Are outdoor conditioning measures of solar control and wind movement enough to improve pedestrians' thermal comfort?
- How long do pedestrians tolerate the lack of shade?

Methodology

Our environment impacts on us in many ways, mostly too complicated to see. These impacts should to a certain extent be investigated in critical and holistic ways to untangle the interconnectedness of the parameters involved. Any change in one or more of the parameters inevitably affects the impact of the whole and can lead to a different behaviour. Therefore, it is very important to look, observe, study and investigate any impact in its precise context and involve as much of the parameters as possible. The way that the impact of the environment is investigated is very significant, if not most critical, to revealing the nature of its impact.

The current research used multiple methods to investigate the influence of the microclimatic conditions as affected by the physical attributes of outdoor spaces on pedestrians' thermal comfort, with the aim of improving the relationship. Within the Gulf region there is very limited current knowledge of such details, which raised the need to employ various techniques and methods to learn about both the microclimatic features of the built environment and the nature of pedestrians in Dubai. An integrated approach, investigating both the built environment and pedestrians comfort, was adopted. The diagram below,

Figure 3, illustrates the four main methods used for the present investigation. Three methods of fieldwork (data logging, interviews and thermal walks) and one method of analytical work (microclimatic simulations) were used. The fieldwork measurements and survey combined static (interviews and data logging) and dynamic approaches (thermal walks), which were then integrated into the analytical method used.

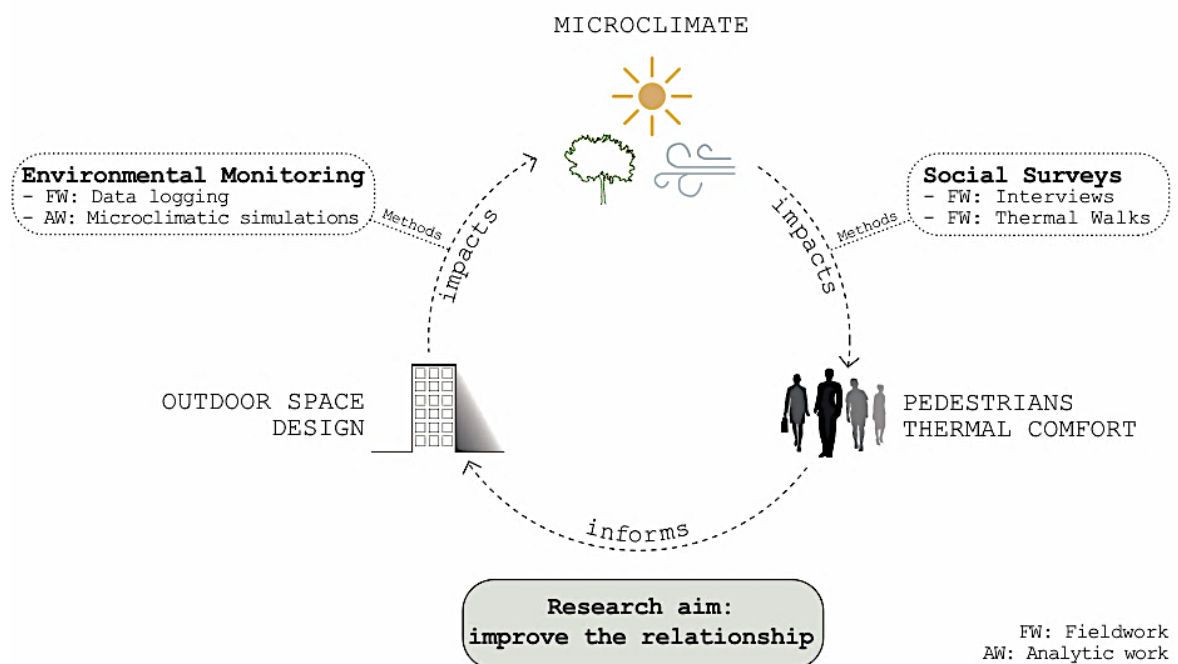


Figure 3 Diagram showing the relationship between the microclimate, the outdoor space design and pedestrians thermal comfort. The diagram shows the methodologies used to tackle each relationship through environmental monitoring and social surveys, indicating the two ways of fieldwork (FW) and two ways of analytical work (AW) followed.

Literature Review

A comprehensive review was made for various studies, books and information that touch on the notion of outdoor thermal comfort, many aspects related to pedestrians, factors that influence walkability and the climatic design parameters in urban space design. This helped to formulate a solid background to the main streams of the topic in hand, which are urban design and thermal comfort. The literature presented in this thesis has been divided into two categories: those that relate to the human parameter, more concerned with the psychological and physiological aspects of pedestrians, presented in chapter two. And those that relate to the physical parameters of the built environment, which tackles the behaviour of the environmental parameters and space composition.

Looking at the theories, principles and tools used to investigate outdoor thermal comfort in hot climates helped to address the critical concerns that refer to pedestrians' satisfaction with their environment. Studies that took static and dynamic approaches to identify comfort also helped to critically examine pedestrians' thermal sensations and comfort during the fieldwork. Studies of thermal transitions were very important in determining the subjective concerns related to the local climate, such as the wide thermal gap between one space and another. This revealed a crucial factor that deeply affected people in Dubai. Furthermore, the theories underlying the creation of walkable urban communities to encourage walkability helped to formulate an idea about the effectiveness of the environmental parameters, as suggested at a later stage of the research.

Fieldwork (FW)

The *interviews* involved questioning random pedestrians along utilitarian routes in authentic urban settings – their daily journeys to work, school, the mosque and the metro – at different times of day throughout the year. The aim was to understand the influence of the environmental parameters on the pedestrians' thermal comfort at different climatic points. The subjective perceptions of thermal comfort and shade were quantified considering the adaptive measures taken to improve people's satisfaction. The metropolitan and transitional nature of the city made it seem useful to gather a range of information about the subjects interviewed, such as their age, gender, clothing, duration of residence in Dubai, etc. The subjective votes of thermal sensation and thermal comfort, based on the ASHRAE (ASHRAE, 1997) scales, were gathered as the spot environmental parameters were recorded. This allowed the study to verify the thermal comfort index Physiological Equivalent Temperature (PET) at a certain stage of research. Information about the shade available in every space was recorded and correlated with the results from the four space typologies monitored using data loggers.

Thermal walks were conducted to identify the maximum distance for which pedestrians could tolerate walking in the sun at different times of the year. Data from fixed points along the utilitarian trips

formed an integral part of the dynamic measurements although the fixed points themselves were static. This approach allowed a simultaneous assessment of the climatic parameters and ensured the stability of the sensors in gauging the climatic measurements. Vasilikou and Nikolopoulou (2014) named this technique 'thermal walks'; it engages pedestrians in trying to understand their surroundings as they walk. An experiment was designed to test the influence of thermal transitions on pedestrians' thermal comfort and thermal sensation levels in different conditions.

The experiment was conducted on the same six volunteers in January, March and May, representing each climatic period in the year. The factors at issue were those known to cause discomfort in the local climate, such as the shift between indoor and outdoor conditions. The experiment observed carefully the influence of the thermal shock to the subjects' tolerance and the thermal sensation felt when moving from indoors to outdoors and the reverse. The effect of moving from shade to sun and sun to shade, including the influence of the wind, was also observed.

Environmental monitoring was used to evaluate the influence of the morphological characteristics of different space typologies on the microclimate, using data loggers. These typologies are representative of the spaces in both the communities selected for investigation and other districts in Dubai. Each space, while similar in its materials, has its own form of solar protection and wind permeability. Accordingly, the heat balance between diurnal gains and nocturnal losses in each space is different because of its geometry, which influences the microclimate and the users. Taking these into account as well provided a better understanding of the use of canopies, trees and buildings to shade outdoor spaces.

Analytical work (AW)

Microclimatic simulations were run using ENVI-met 4.2 for the JLT urban area to comprehend the influence of the morphological characteristics at different spaces along pedestrian's routes of on a larger scale. The microclimatic parameters (air temperature and relative humidity) measured during the environmental monitoring fieldwork were compared to those extracted during the simulations to validate its usage under the local climate. Other parameters such as the mean radiant temperature and wind speed were extracted from the simulations at different months throughout the year.

The proposed intervention

Numerous findings from the fieldwork were analysed and interrelated. Key findings, which were found to be the most influential in improving pedestrians' comfort, were incorporated in an intervention proposed at the end of this thesis. This proposal for improving thermal comfort is accompanied by a set of design guidelines and presented in a physical paradigm shown as an enhanced scenario. The

enhanced scenario was tested using ENVI-met and compared with the existing conditions of a utilitarian route, providing evidence and validation of a way to improve pedestrians' comfort and encourage walkability in urban communities in Dubai for longer periods every year.

Thesis outline

The thesis digests the wide diversity of existing theoretical knowledge about the dynamics of outdoor thermal comfort, focusing on its direct application to pedestrians. The study takes the previous practices and research and investigates the possibility of improving pedestrians' comfort in urban settings in Dubai. The body of the text is organized in four parts, listed below:

PART I: CONTEXT OF THE RESEARCH this section illustrates the climatic and contextual background of Dubai and the topic in hand. Objective arguments are formed from the literature.

Chapter 1 The climate: provides a detailed description of the climatic conditions in Dubai demonstrating the annual classification adopted in this thesis. It highlights the climatic period aimed for improvement.

Chapter 2 Pedestrians' thermal comfort: addresses the factors affecting people's thermal comfort outdoors, focusing on the characteristics of the thermal environment that relate to pedestrians.

Chapter 3 The microclimate of Urban Spaces: reviews the literature which exploits the diverse attributes of the built environment that aims to cool the microclimatic conditions considering the multiple methodologies used.

PART II: FIELDWORK AND ANALYTICAL WORK this section explains the fieldwork and the analytical work carried out to investigate the relationship between pedestrians' thermal comfort and the built environment.

Chapter 4 Social surveys 01: setting the comfort limit: describes the interviews carried out to quantify pedestrians' thermal sensations and set the comfort limits in Dubai at different months.

Chapter 5 Social surveys 02: thermal walks: describes the experiment that has been structured to test the influence of thermal transitions on pedestrians' comfort in an actual urban setting.

Chapter 6 Environmental monitoring and simulations: overviews the 12-month process of measuring the outdoor parameters in several outdoor space typologies, with the aim of understanding the behaviour of the space morphology throughout the day and year.

PART III: THE PROPOSED METHODOLOGY this section compiles significant findings revealing the convenient ways to improve pedestrians' comfort in this climate.

Chapter 7 Thermal comfort recovery conditions presents the speculative method developed to improve pedestrians' thermal comfort and allow them to walk for a longer period every year. The microclimatic simulations run to test the proposal was demonstrated comparing it with the status quo.

PART IV: CONCLUSION this last section summarizes the various findings of the study highlighting the way to improve pedestrians' thermal comfort. The research challenges, limitations and potentials for future development were also presented.

PART I: CONTEXT OF THE RESEARCH

CHAPTER 1: The Climate

Dubai, one of the seven constituent parts of the United Arab Emirates (UAE), lies on the southeast coast of the Persian Gulf (25°N 55°E). The proximity of the seven emirates creates great similarity between their topography and climatic characteristics. Climatic data for the city of Abu Dhabi were used in the climatic analysis presented in this chapter to overcome the lack of data and weather files for Dubai. The very little research and few studies, aggravating the need for a detailed analysis of the climatic parameters that most influence pedestrian journeys outdoors. The chapter illustrates the climatic classifications of the different seasons each year.

1.1. Climatic parameters

1.1.1. Air temperature

Generally, Dubai has a hot climate with high humidity levels. The annual mean air temperature cycle moves smoothly between the different months, recording its lowest values in January and its highest in August, as shown in

Figure 4. There is a wider shift of 5°C only in the minimum values between March and April, leaving the average daily values unaffected. The diurnal air temperature values show a wide range, between 17.4° and 26.8°C, in the minimum and maximum values in both January and March (Ministry of Presidential Affairs 2016). This is due to the effect of the high levels of solar exposure.

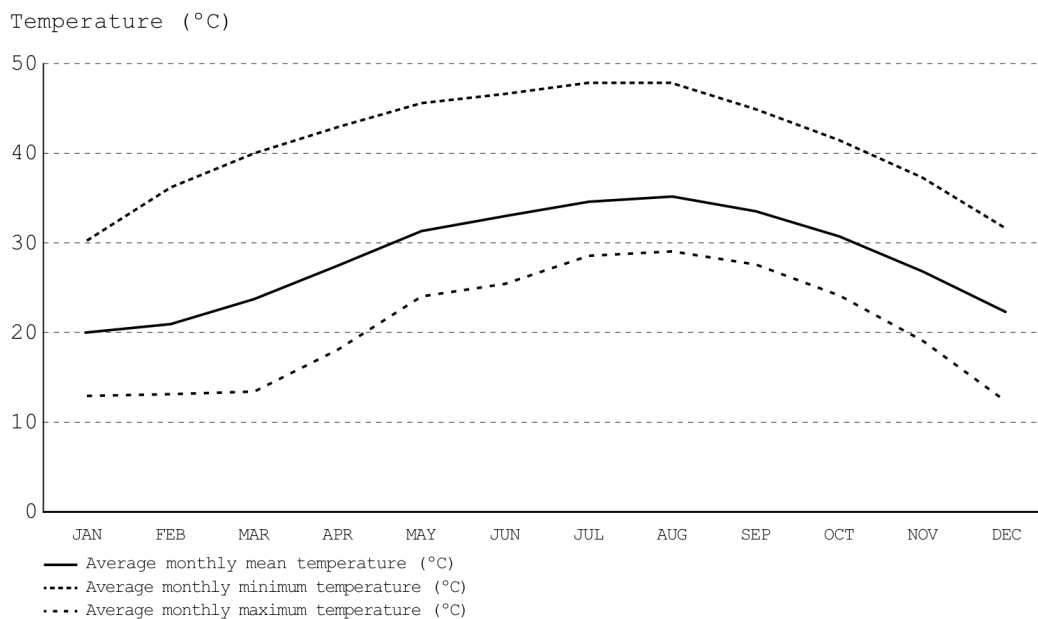


Figure 4 Graph illustrating the average monthly mean minimum, maximum and average air temperatures.
Source: Ministry of Presidential Affairs (2016)

1.1.2. Air humidity

Humidity is indicated by the amount of water vapour in the air. The water vapour particles affect the irradiance levels of sunlight, which influences the amount of heat trapped in the air, resulting in an increase in the mean radiant temperature. Relative humidity is the ratio between the amount of water held in the ambient air and the amount it could hold at the same temperature. As the temperature changes during the day, the relative humidity also changes substantially, even when the water content remains constant. In the local climate, the annual monthly mean relative humidity values range between 79% in March and April and 83% in January and February, as shown in Figure 5 (Ministry of Presidential Affairs, 2016). More diffraction is also the result of more water vapour particles in the atmosphere. However, wind speed has a reverse effect on relative humidity, which in turn affects the received irradiance.

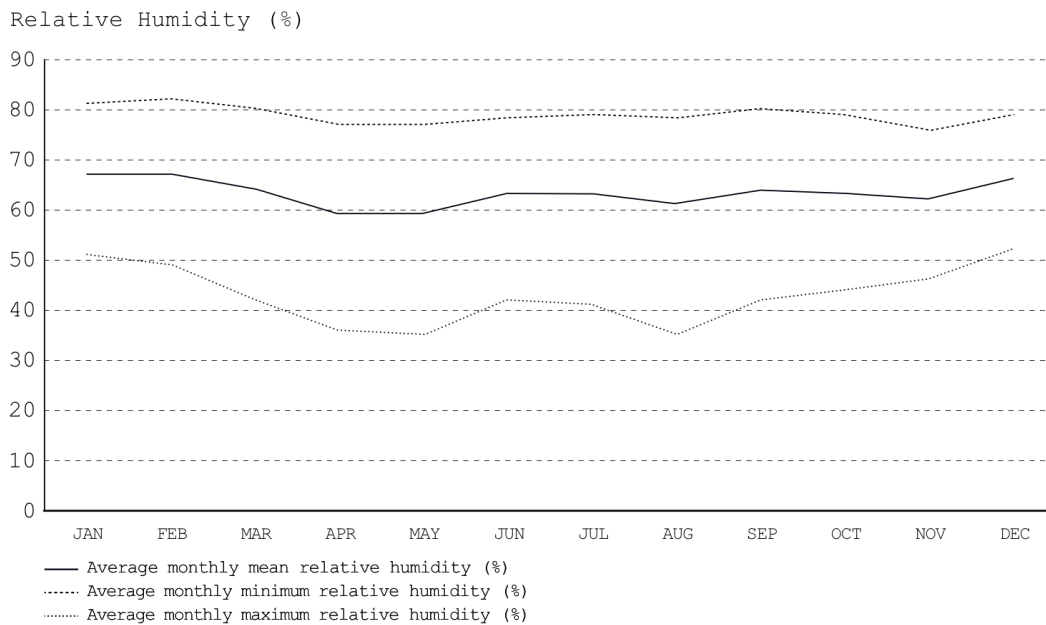


Figure 5 Graph showing the mean minimum, mean maximum and mean relative humidity. Source: Ministry of Presidential Affairs (2016)

1.1.3. Solar radiation

The UAE lies between 25°15' North in latitude and between 55°18' East in longitude, which indicates a high solar energy exposure. However, high concentrations of airborne dust particles and high humidity tend to diffuse and attenuate the intensity of the solar irradiance (Mokri et al., 2013). The mean solar radiation is 5970 Wh/m² in March, when clouds and rain are expected. The mean highest value of solar radiation throughout the year is 6850 Wh/m² in May, as shown in Figure 6, with 11.3 hours of sunshine per day. In December, sunshine hours drops to 7.6 hours per day and records the lowest value with 4180 Wh/m² (Ministry of Presidential Affairs, 2016 and Abdalla and Feregh, 1988).

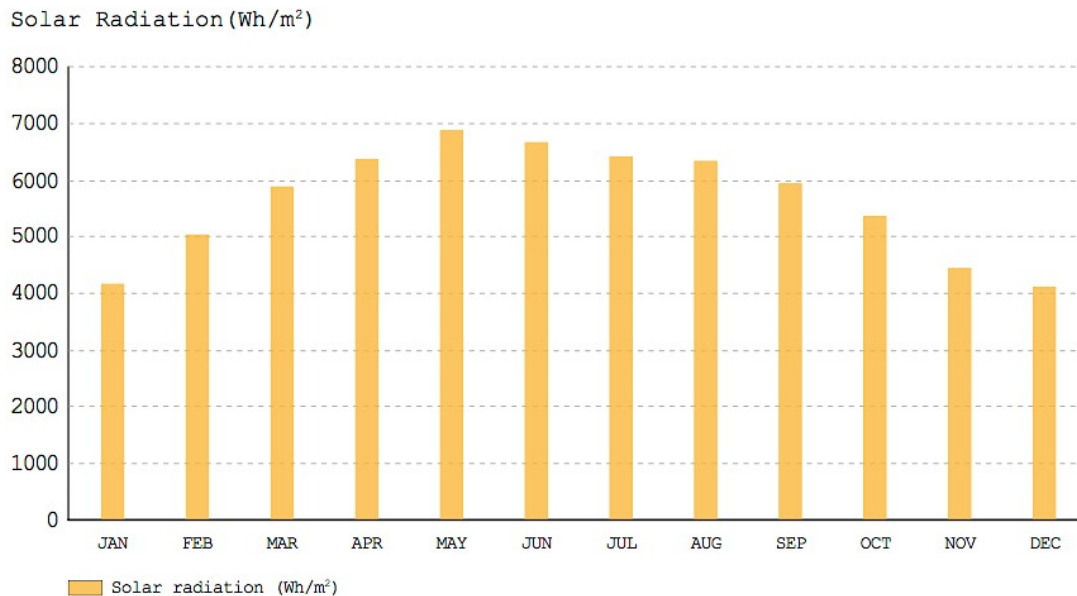


Figure 6 Graph showing the solar radiation during the different months throughout the year. Source: Ministry of Presidential Affairs (2016)

1.1.4. Wind speed

Local north-westerly winds shown in Figure 7, locally referred to as the ‘Shamal’, frequently develop during the winter, bringing cooler windy conditions. Early mornings in Dubai bring calm or a slight southerly wind offshore. At some point from about 10:00-11:00 am, the wind turns north westerly and blows onshore. Usually the average strength of the prevailing wind in Dubai is about 8.5 mph (3.8 m/s). Occasionally, a *Shamal* can blow in from the desert – from a southerly or south-easterly direction, which is opposite to that of the prevailing wind in Dubai. The minimum and maximum wind speeds in December are 6.66 mph (2.98 m/s) and 13.75 mph (6.16 m/s) respectively, whereas in the month of June; they tend to be 8.39 mph (3.75 m/s) and 15.66 mph (7 m/s) respectively (Al-Sallal and Al-Rais, 2012).

Stronger winds commonly blow a good deal of dust and sand into the atmosphere. Very occasionally, this can turn into a full-blown sandstorm but it is rare for it to last more than a few hours (National Media Council, 2015). Winds increase significantly in April, October and November and slow down significantly in August (the hottest month), as shown in Figure 7. The months with higher wind speeds are those when the weather gets warmer, but the wind can be used to improve pedestrians’ thermal comfort. In the other months, the wind speed levels remain close to these figures.

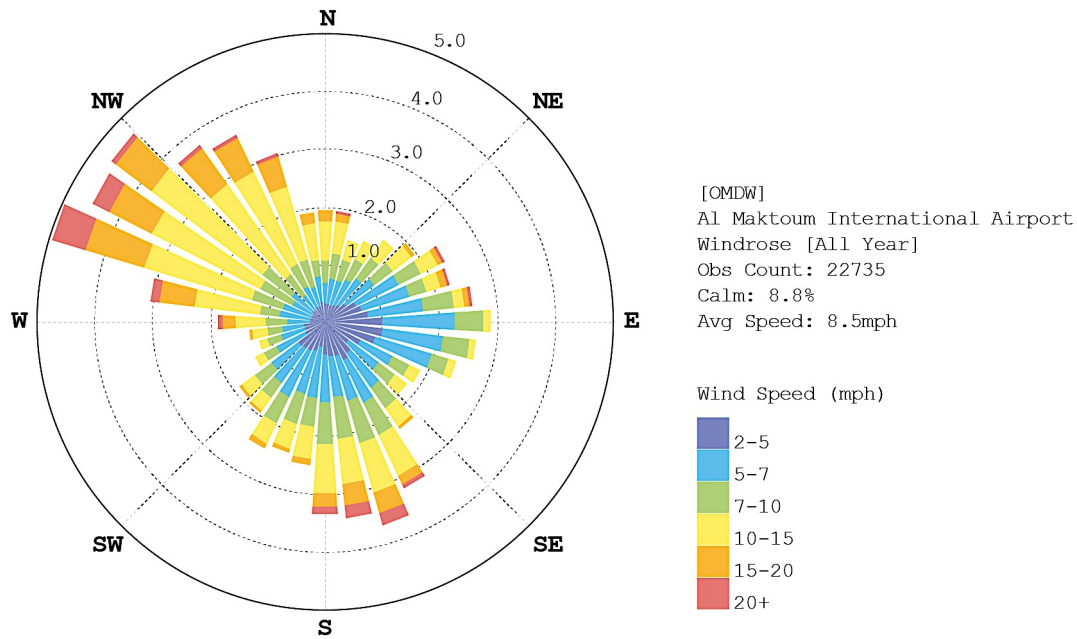


Figure 7 Wind rose diagram showing the yearly wind direction and average wind speed in Dubai all year.
Source: National Media Council (2015)

1.1.5. Precipitation

Rainfall in Dubai is sparse and intermittent, usually occurring during the winter months of February or March. Winter rains take the form of short sharp bursts, which, if they occur in the *Hajar Mountains*, run off rapidly into *Wadis* and onto the down-washed gravel plains. Localised thunderstorms occasionally occur during the summer (Ministry of Presidential Affairs, 2016). However, in 2010, a US\$11 million project of cloud seeding was launched by the weather authorities to create rain artificially. The National Centre for Meteorology and Seismology (NCMS) successfully created rainstorms for a few days in the Dubai and Abu Dhabi deserts in the last two weeks of April 2014 and April 2015 to supplement water supplies. Cloud seeding was already 30% more frequent in 2013 than in the previous year. This has contributed to many cloudy days, hence smaller solar gains in March and April 2016. Therefore, it is important for future planning to anticipate the weather-proofing measures that can maintain walkability in these two months, such as the provision of rain gutters on walkways and structures for sheltering pedestrians.

1.2. **Classification of the climatic periods**

Statistical analysis was carried out using a tool developed earlier by the Sustainable Environmental Design (SED) studio at the Architectural Association School of Architecture, to demonstrate the outdoor parameters that most inhibit adaptive comfort. Raw climatic data files for Dubai obtained from the SDBE MSc programme in the British University in Dubai, were imported to an excel sheet

created by the SED studio at the Architectural Association in 2014. The yearly climatic conditions were divided into three distinct periods based on Yannas (2008) classification: the four-month period of mild weather, December to March inclusive; two warm months, November and April; and a hot period, May to October inclusive as shown in Figure 8. An adaptive comfort band of 7°C, shown below, based on the ASHRAE standard 55 (Brager and de Dear, 2001), reveals an overview of the thermal comfort levels expected in different months. The range is considered narrow when compared to people's tolerance of heat in hot climates and in the UAE (Balakrishnan, 2012; Yannas, 2008; Thapar, 2007). But there is still a lack of tools with which to predict thermal comfort that can be validated in Dubai's climate, a lack which will be tackled during field investigations.

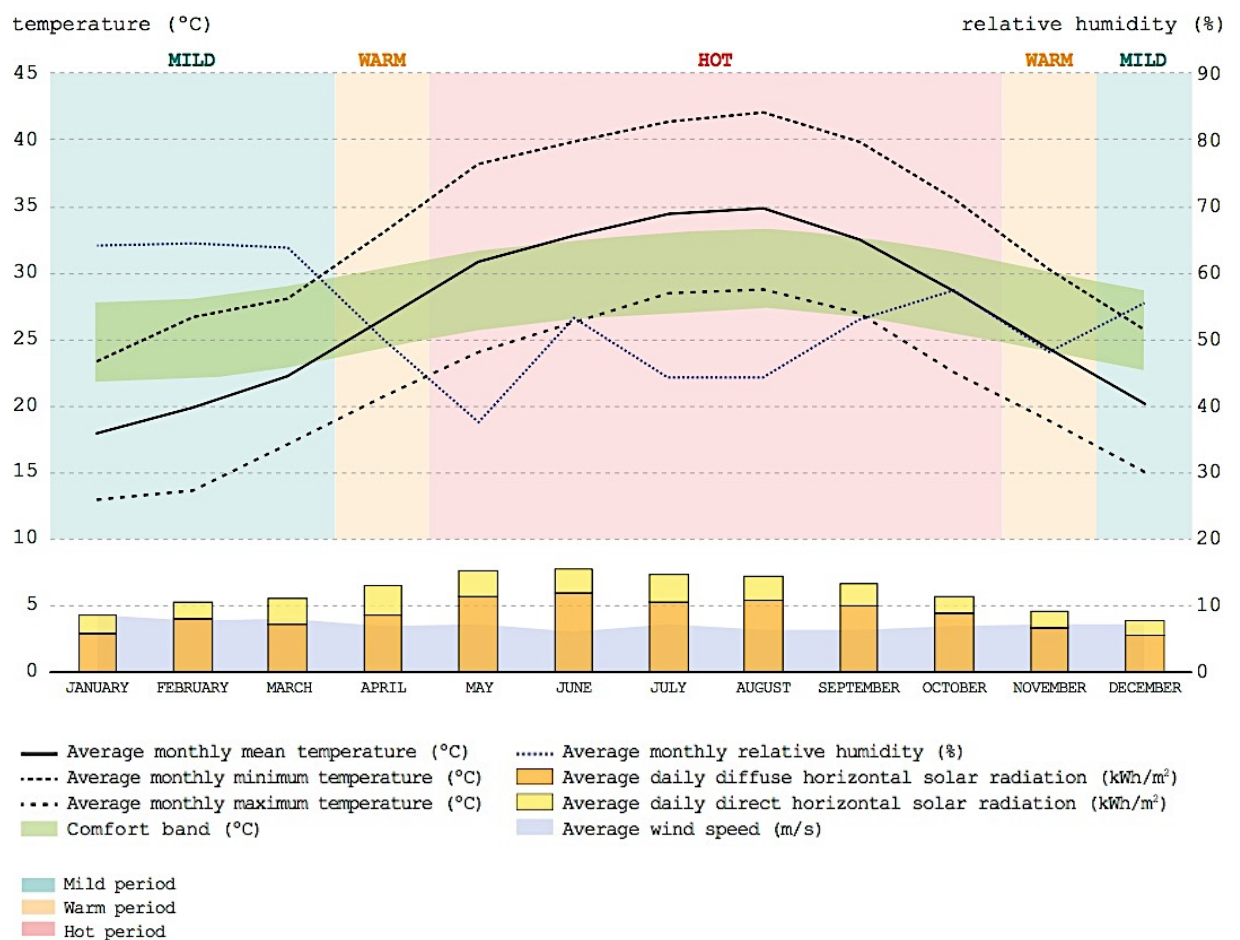


Figure 8 Graph showing the year's monthly mean air temperature in the three climatic periods, warm, mild and hot. Source: SED studio at the Architectural Association

1.2.1. Mild period

During the mild period, the average monthly mean air temperature ranges between 20^o and 24^oC, the maximum values between 30^o and 40^oC and the minimum at 13^oC. These months feature pleasant outdoor conditions when pedestrians enjoy walking, whether it not protective measures are provided by the built environment. The use of outdoor spaces revives; many different activities, allowing social interaction and cohesion. However, in the early mornings of January and February, as the minimum air temperature values drop below the comfort range, shaded areas and strong breezes are not favoured, which should be considered when planning shade in outdoor spaces. Discomfort, even for short periods, should be avoided. Pilot fieldwork revealed that pedestrians walking to school, work and metro stations took some adaptive measures, wore jackets and avoided shaded pathways. The present research aims to extend this period and allow pedestrians to walk outdoors in the same way for longer periods elsewhere every year.

1.2.2. Warm period

During a warm period, the average monthly mean air temperature ranges between 27^o and 28^o, the maximum values between 37^o and 43^oC, the minimum between 18^o and 19^oC. In these months, pedestrians start to experience discomfort due to the increase in temperature and humidity levels. Thermal comfort during this period can be considered to occupy a 'tolerable zone' where the comfort levels can be met if the built environment offers proper measures of climate proofing. Pedestrian patterns during these months continue at the same pace along certain routes where shade prevails or during the evening. A related aim of this research is to improve the thermal environment by measures to encourage shade and air movement, in order to provide similar conditions to those of the mild months.

1.2.3. Hot period

In a hot period, the average monthly mean air temperature ranges between 31^o and 35^o, the maximum values between 42^o and 48^oC and the minimum between 24^o and 29^oC. There is a rapid increase in air temperature and humidity values between May and October, reaching a peak in July and August. During these two months, the outdoor conditions become intolerable for most pedestrians. At midday, exposure to direct solar radiation should be avoided, to prevent sunstroke (Islam et al., 2009). Moreover, the high temperatures and relative humidity during this period dramatically increase the discomfort – due to the reduction of water in the body from evaporative heat loss – which can be held responsible for the ubiquitous dependence on artificial cooling.

The distances that pedestrians travel during this period shrink dramatically but do not vanish altogether; the air temperature sometimes remains tolerable for short periods of exposure. However, earlier studies (Balakrishnan, 2012; Al-Sabbagh, 2011; Thapar and Yannas, 2008) reveal that, so long as direct solar exposure is avoided, outdoor cooling is possible even in this period. The aim of this study is to shrink this period overall by improving the thermal environment, particularly in May, September and October, to increase the few pedestrian patterns now discernible. The thermal comfort band during these months in some respects parallels the climatic conditions in the early morning and late afternoon. Therefore, the hot period has been subdivided into two parts, hot (May, September and October) and extremely hot (June, July and August), as seen in Figure 8.

1.3. Conclusion

From general observation and the climatic analysis conducted, the reason for Dubai's reputedly harsh climate can be summarized as follows: a hot six-month period of May to October, with its extremes of high temperatures and high humidity levels and a further six months in which the weather is pleasant for four months and tolerable for two more. This highlights the potential for encouraging walkability by suitable and efficient measures of solar protection and ventilation. The design of urban communities in Dubai needs to consider features that improve the microclimatic conditions, providing flexibility to accommodate the climatic changes each season. Although too little has been discovered about the influence of climatic conditions, the current study aims to shrink the hot period and extend the mild and warm periods for pedestrians by improving their thermal comfort through efficient measures of solar control and airflow. This would in turn encourage walkability and extend the period when the inhabitants of Dubai can enjoy the outdoors.

CHAPTER 2: Pedestrians' Thermal Comfort

Thermal comfort significantly influences the way in which people respond to their environment. The design of this environment articulates the microclimate, which controls people's behaviours within. The relationship between people and the built environment can be understood further by investigating outdoor thermal comfort. Over the past century, attempts to define 'thermal comfort' have slightly differed from one another, bearing in mind the wide variation of parameters it involves.

Experts from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provided a definition that has been accepted globally and used repeatedly: "the state of mind that expresses satisfaction with the thermal environment" (Brager and de Dear, 2001). Hoppe (1993) considered this definition more descriptive of a 'psychological approach' to investigating thermal comfort. The subjectivity and the wide diversity of what satisfies individuals makes the term qualitative and brings in behavioural aspects, which not only differ between people from different places, but also people from the same area. Appreciating the fundamental impact of people's psychological parameters, such as their expectations and preferences with regard to their surroundings has been considered the 'adaptive model' approach to thermal comfort (Brager and de Dear, 2001). This model centres on the behavioural and subjective assessments of individuals in real settings and reflects more than the physical relationship between people and their environment.

Many others have used the above definition of comfort to set out models, which mimic the physical environment and physiological conditions to predict comfort levels, quantitatively producing a good number of thermal indices. These models, known as 'heat balanced models', rationally analyse the heat flow between the human body and its surroundings, based on physics and physiology (Nicol et al., 2012). Comfort is calculated on the basis of mathematical equations derived from the responses of the human body to its physical environment. The input of certain climatic parameters, such as the air temperature, air velocity, mean radiant temperature and relative humidity, along with other personal factors such as age, gender, activity and clothing are used to predict thermal comfort. The most widely known of the attempts to do this is the Predicted Mean Vote (PMV) model (Fanger, 1970), the basis of most national and international comfort standards (Nicol et al., 2012), and the Standard Effective Temperature (SET) (Gagge et al., 1986). Further discussion of thermal indices can be found in the following sections, identifying those used for outdoor environments and focusing on those developed to suit pedestrians' changing conditions as they move across different spaces.

Earlier studies on outdoor comfort focused either on people who approached the outdoors to sit/stand in a park or plaza, or on those who walked either for enjoyment or to reach a specific

destination. Although the outdoor parameters involved in both categories may seem similar, yet the personal factors are not. The state of physical activity is different for people sitting or resting and those walking: the latter experience higher metabolic rates, which require lighter clothing or a higher wind speed to compensate for possible discomfort. This is due to the mechanism of the human body as it tries to reach a state of equilibrium with the surrounding environment.

The human body takes part in a constant heat exchange with its surroundings. While the exchange lasts, people go through physiological processes that they are unaware of, but they make conscious behavioural responses to achieve or maintain thermal comfort. All the factors that are involved within this process can be sorted into three main categories: environmental, psychological and physiological factors. When investigating thermal comfort, it would be ideal to bring every relevant factor, but the numerous parameters involved make this impractical. At the same time, it is inadequate to investigate any of these factors in isolation from the rest, since it is their interconnectedness that accounts for our overall satisfaction (Gaitani et al., 2007). These factors are discussed in this chapter, highlighting their prominence in this research.

2.1. Dynamics of the human body

2.1.1. The physiological balance

In any physical state, our bodies automatically tend to maintain an almost constant internal temperature around 37°C, irrespective of our environment, to maintain our physical and mental health. Our thermal interaction with the environment is directed towards maintaining this stability in a complex and dynamic process called ‘thermoregulation’ (Nicol et al., 2012). The thermoregulatory process is a combustion process that our bodies experience – converting food to produce energy. During this process, a good deal of heat is emitted, adding up to the amount produced when we perform any sort of activity such as walking, sitting, singing and even thinking. Usually, the more muscle works the activity requires, the more heat is produced. A reclining person may produce 40 W/m² while a sprinter generates over 400 W/m² (Brager and de Dear, 2001). The body’s internal heat is transported around the body through the blood, which is then transmitted to the cooler environment in the form of heat loss. If the temperature of the surroundings is higher than that of the mean skin temperature, the cycle is reversed and the body gains heat.

Thermoregulation between the human body and the environment has four transfer modes: convection, evaporation, conduction and radiation. The body absorbs heat from direct solar radiation and long-wave radiation from its surrounding surfaces and the sky. It loses heat through convection due to air temperature differences and wind flow, and through conduction to the surfaces that it

encounters. In addition, when perspiring, the body loses heat through the evaporation of sweat on the skin.

In hot or cold environments, the thermal conditions sensed by the human body enter indirectly through the nerve endings named the thermoreceptors. These then send signals to the base of the brain, named the hypothalamus. These signals allow us to perceive the thermal condition of our surroundings according to our thermal sensations. Thermoreceptors are distributed around the human body but mainly in the periphery of the body and in the forebrain, protected through the skin tissue (Zhang, 2003). Some thermoreceptors are more sensitive to cold while others respond rapidly to warmth. Therefore, in cold conditions heating the palm of the hand can make us feel warmer, though the converse is not the case. This is explained more detail in section 2.7.2, where the most effective body parts to cool are reviewed in order to understand how to improve thermal comfort.

2.1.2. Skin temperature and skin wetness

Skin acts as a conductor between the human body and the environment. It is the primitive tissue through which the warmth or coolness that surrounds us makes its way to the thermoreceptors. Metje et al. (2008) have argued that the skin temperature can serve to indicate the heat exchange between a person and his environment and the thermal sensation that an individual is experiencing. It is greatly influenced by the environmental conditions and the surrounding parameters (Mehnert et al., 2000). Skin temperature represents local thermal conditions for the skin, while the body core temperature represents the whole body's thermal status (Bulcao et al., 2000).

In warm conditions, the skin blood flow increases as the blood vessels widen to allow a convective loss of the heat transferred to the skin surface. This exchange depends on the environmental parameters, such as the air temperature, relative humidity and wind speed surrounding the human body. Other endogenous factors are also involved such as the core temperature, skin conductance and blood flow rate (Mehnert et al., 2000). When the body is too hot – exposed to heat for a long time, exposed to high heat levels, or in motion – the “heat loss centre” in the brain sends out signals to initiate the body's heat loss mechanisms of vasodilatation and sweating (Zhang, 2003; Bulcao et al., 2000). In other words, a person who has an elevated core temperature will sweat because of the activity of the heat loss centre; but once his skin temperature is lowered by cooling, the brain signals will be stimulated so that sweating diminishes or stops (Zhang, 2003).

The skin temperature is lowered by cooling through evaporative heat loss, a process which is greatly influenced by three factors: the exposition of the skin (clothing), the air movement (wind speed), and the saturation of air with water (humidity). Clothing blocks the wind's penetration to the skin surface,

thus allowing a lower rate of evaporation to take place. There is a strong relationship between the clothing weave and air velocity, where the looser the weave of fabric in the clothes the more ventilation occurs on the skin's surface. In humid conditions, the relative humidity reduces the evaporative heat losses occurring at the skin surface, worsening the thermal sensation and comfort levels. However, stronger winds could compensate for this effect.

The heat load varies across the parts of the body due to the amount of exposure given to the skin. Therefore, in the same environmental conditions the skin temperature of different parts of the body varies. Qualitative comparisons of different skin segments and their responses are detected thermographically, scanning the SBF through infrared radiations. A few studies (Zhang, 2003; Tsuchida, 1979; Gagge et al., 1967) have looked for a relationship between the SBF and the skin temperature when exposed to different forms of cooling that are aimed at correlating the skin temperature and the environmental conditions.

These studies have found that discomfort correlates best with a reduction of the average skin temperature in a cold environment and with increased sweating in a hot environment. This means that skin temperature is more indicative of the thermal sensation in cold conditions than of that in warm conditions. This is due to the physiological response of sweating. When the body faces a thermal stress, its physiological response (sweating) prevents the skin temperature from increasing. Since, the sweat level is so different from one person to another, threshold is widely variant. The temporal shift in the metabolic rate of the subjects in response to their physical status and their interaction with their environment sometimes interferes with the physiological evaluation notwithstanding gender-specific differences (Chen et al., 2011).

It was also found that such responses also differ when moving from cold to warm conditions, where the rate at which the skin temperature rises causes a sensation that compensates for and predominates over the sensation of discomfort caused by the low skin temperature itself (Gagge et al., 1967). However, it is noteworthy that the adaptation rate of human skin in hot conditions is much faster than the adaptation rate of the body's core (Katavoutas et al., 2015; Chen and Ng, 2011; Höppe, 2002). The sensor-resembling and fast-reacting characteristics of skin temperature responding to microclimatic change render it a unique property that perhaps is more closely associated with reflecting environmental change than with indicating the corresponding thermoregulatory adjustment (Chen et al., 2011).

Earlier studies investigating the influence of changes in the thermal environment on the skin temperature (Stolwijk, 1979) note the delay in the change of skin temperature when moving from a

cold to a warm environment. Changes in the thermal sensation were faster than in the skin temperature of the subjects tested. This suggests that the dynamic response of thermoreceptors to changes in temperature is capable of anticipating the body's steady-state response to a new thermal environment well before the body's heat content has time to alter significantly (de Dear et al., 1993). Gagge et al. (1967) calls this phenomenon "anticipation". It follows that instantaneous or subliminal variations within the thermal environment may not be reflected strongly in physiological changes of the skin unless enough time is given for this organ to adapt. Yet it is important to conduct such measurements to the skin parts that are fully exposed to the thermal environment, such as the dorsal skin of the left arm (Chen et al., 2011). It is important also to make minimal movements, since it was found that movements increase the blood flow and thus affect the results of skin temperature.

Blazejczyk (1997) points to the significance of evaporative cooling on body temperature regulation, especially at higher metabolic rates such as are attained during exercise. The study reveals that in the same microclimatic conditions a pedestrian's skin temperature is mainly influenced both by direct solar radiation and by evaporation of sweat from the body surface. Cloudy conditions reduce the skin temperature of standing subjects by 5-6°C. It was also shown that the skin temperature of a person standing or resting in the sun gradually rises, while someone who is walking or running will not have a higher skin temperature due to the presence of sweat. Field measurements were taken in June and August 1996 in Central and Southern Poland on six subjects, whose ages ranged from 16 to 46 years. Solar exposures lasted 120 min. Subjects stood upright facing the sun; after 60 min, they sat for 5 min and then stood for 55 min. Their skin temperature was measured every minute with the use of resistant (Pt100) thermometers connected to the forehead, arm, chest, back, hand, thigh and lower leg.

The direct correlation between the skin temperature and thermal sensation has been widely demonstrated through research. This gives an idea of the way in which the human body reacts to the thermal signals given from the surrounding thermal conditions, identified as thermal sensation and thermal comfort. The physiological process is more indicative to the mean skin temperature in cold conditions and to the wetness of the skin caused by sweat secretion in warm conditions. To estimate mean skin temperature, using measurement locations throughout the body, weight must be given to each part depending on the weighing factor models developed. However, it is important to measure the most relevant body parts based on the climate, when depending on skin temperature for a clue to thermal sensation (Zhang, 2003).

2.1.3. Activity level and clothing

The human body uses physiological processes (e.g. sweating, shivering and regulating the blood flow to the skin) to maintain a balance between the heat produced by metabolism and the heat lost from the body. The heat produced by the body is quantified according to the level of its activity while the heat lost from the body is influenced mainly (but not only) by the clothing values. This is to maintain a heat balance as the first condition and achieve a neutral thermal sensation (Charles, 2003). Therefore, for accurate predictions of comfort, the metabolic rate, as indicated by the activity level, should be measured precisely (Havenith et al., 2002).

The energy required by the human body to perform any sort of activity is produced by using food and oxygen in a process known as the metabolism. The rate at which this process occurs is called body's metabolic rate (M). Heat is exerted along the process depending upon the intensity of the mechanical work (W) performed thus the amount of energy required and is measured by the metabolic heat production (H). The value of the heat can be calculated through the formula: $H = M + W$. For someone performing a sedentary task such sitting in an office, W could be regarded as 0, thus the heat produced will be equivalent to the body's metabolic rate (Havenith et al., 2002).

Pedestrians feel this even more acutely, since walking increases their activity level and in turn the heat produced by the body raising their metabolic rate. The higher the metabolic rate, the higher the associated thermal stress, because the heat that should be dissipated to achieve thermal comfort becomes greater. In Dubai, this is even magnified by the lack of shade, wind and the increase of humidity, which is fundamentally required for people in motion. The metabolic rates rise by 11% for all activities performed in temperatures as they rise from 21.2°C to 37.8°C, but providing shade even without any reduction in air temperatures reduces the metabolic rate by 2%-5.2% below that when same activity is performed in sunshine (Givoni, 1976). Therefore, a person walking in the sun is expected to feel the heat stress far sooner than if he were walking in the shade.

At the same time, the body's energy balance depends on our clothing insulation (Auliciems and Szokolay, 1997). Clothing reduces the body's heat loss and therefore, it is classified according to its insulation value. The unit normally used for measuring the insulation capacity of clothing is the clo unit. The lowest clo value is zero for the naked body. On average, the summer clothing value is around 0.6, while the winter clothing value is around 1.0. In outdoor spaces, people's clothing is an adaptive measure, allowing them to alter what they wear to cope naturally with their situation (Gaitani et al., 2007). A wide variety of clothing is worn by pedestrians in Dubai. At 24°C some people wear jackets and trousers (1.2 clo), while others wear half sleeves and shorts (0.7 clo). The diversity of backgrounds of the city's inhabitants makes it an even greater challenge to identify an average clo value.

Ghaddar et al. (2011) find that in warm conditions, with temperatures ranging from 26°C to 30°C, low permeable clothes cause pedestrians to feel thermally uncomfortable. The study also demonstrates that allowing higher permeability fabric material for the torso only improves the thermal sensation to an acceptable range of PMV. This happens when the wind speed increases circulation from 1 m/s to 1.5 m/s. Thus, in hot humid conditions, the heat transfer from the human body to the environment along with the wetness of the skin requires low vapour resistance clothing to be worn (ISO 9920). The effects on thermal comfort of reductions in vapour resistance due to air and body movements have a substantial impact on the comfort limits in terms of skin wetness and should not be neglected (Havenith et al., 2002).

2.2. Psychological adaptation

People's satisfaction with their surroundings differs from one place to another, depending on a number of subjective parameters. In 1980, Rohles (Rohles, 1980) showed that simple changes within the interior finishes and furniture, such as using wood and carpet, even at the same thermal conditions, made occupants feel warmer than they felt in tests without them. Merely telling occupants that the temperature was higher than it really was immediately already made them feel warmer. In wintertime, people tended to prefer warm temperatures to cold ones, while in summertime the case was just the opposite. Höpfe (2002) argues that this is due to psychological parameters, which play a significant role in people's comfort levels both outdoors and indoor.

Psychological adaptation has a crucial role in improving people's satisfaction with their surroundings. Once people have decided to leave their houses and sit outside, they have accepted various facts about the thermal conditions and are prepared to accommodate them. The physical environment and psychological adaptation are argued to be complementary rather than conflicting, and the exploitation of this relationship could revitalize the city's open spaces and increase the social interaction between the inhabitants. The physical approach in order to predict thermal comfort, measures the microclimatic conditions that result from the attributes of the built environment. However, it only accounts for around 50% of the variation in the interviewees' thermal sensation. The rest could not be measured by physical parameters, but psychological adaptation seemed to become increasingly important (Nikolopoulou and Steemers, 2003).

The large research project, RUROS, which investigated outdoor thermal comfort in Europe, is concerned with the environmental conditions for people in public open spaces. It distributed nearly 10,000 questionnaires in 14 different sites across five cities. Nikolopoulou and Lykoudis (2006) and Nikolopoulou et al. (2001) recommend a number of things and present the findings, one of which is that a purely physiological approach is inadequate to characterize thermal comfort conditions

outdoors. The psychological factors in play were summarized as 'available choice', 'environmental stimulation', 'thermal history', 'memory and expectation', 'the naturalness' and the 'time of exposure'. However, it is essential that architects and urban planners understand the nature of each of these factors to enable them to identify the challenges that pedestrians face when venturing outdoors.

People perceive spaces differently; their thermal perception is influenced by the information they have of a particular experience. Their 'memory' about the space influences their 'expectation', which is a typical form of psychological adaptation (Zambrano et al., 2006; Nikolopoulou and Lykoudis, 2006). An investigation of the relationship between expectation and thermal comfort asked people in a more northerly city than Dubai why they felt comfortable when the temperature was above the comfort zone. They stated that the weather had been unseasonably cold on the days before the interviews, so, they were happy the sun shine, taking time off, and get sun-tan (Höppe, 2002). Conversely, during the extremely hot summers in Dubai, Thapar (2007) has found that when the air temperature was 40°C people reported that they coped well with being outdoors. Al-Sabbagh (2014) explored this further during the same conditions and revealed that many pedestrians remarked that the outdoor conditions were better than they had anticipated. Sometimes, expectation can increase people's tolerance of outdoor conditions.

Höppe (2002) reviewed findings from a former study Kotz (1984), which highlighted the influence of expectation on people's tolerance to heat. 250 passers-by in a sunny street canyon and on a lawn in a park interviewed on a hot summer day voted that they felt very comfortable. According to the PMV-index (Fanger, 1970), they were expected to vote 'hot' or worse. Höppe highlights the importance of the psychological factor in thermal comfort which forms people's perception to the thermal environment and is echoed by other writers (Nicol et al., 2012; Lin, 2009).

An analysis of perceived control suggests that when individuals autonomously chose to visit the square, for instance to walk or rest, their satisfaction levels with the thermal environment were high. Conversely, when the level of autonomy was low, i.e., when people had to pass through the square, their levels of satisfaction were low. In terms of behavioural adjustments, seeking shade was the preferred adaptive behaviour. These analytical results demonstrate that the thermal perception of respondents visiting the square was affected by thermal environmental factors, and by psychological and behavioural factors, thereby confirming the existence of thermal adaptation in a hot and humid region (Lin et al. 2011).

Another psychological factor of thermal comfort is the 'thermal history' of the people, that is, the climatic conditions that an individual has adapted to for the past few years. For example, Taiwanese people prefer warmer conditions to those chosen by European nationals, due to the climatic conditions that each group has become accustomed to (Lin et al., 2010). Lin (2009) finds that the thermal comfort of respondents in Taiwan was 21.3° - 28.5°C PET, significantly higher than that reported in Central Europe (18°-23°C). The Taiwanese most preferred 24.5°C PET in the hot season and 23°C PET in the cold season. Analysis has found that psychological and behavioural adaptation greatly influences people's satisfaction with the thermal environment. This makes thermal comfort very challenging to predict and investigate in metropolitan cities due to the diversity of thermal backgrounds.

Lin et al. (2015) also compares people's thermal perception in Lisbon and in Taiwan through field measurements and surveys. The results of analysing the overall thermal comfort dissatisfaction indicate that people in Taiwan have higher tolerance than people in Lisbon of thermal comfort conditions (e.g. PET). However, people in Lisbon have higher tolerance of wind speed than those in Taiwan. These results can be explained by the long-term climatic conditions; Taiwan has higher air temperature, humidity and global radiation, while Lisbon has higher wind speeds. The results display the thermal adaptation to be expected in different areas and reveal that in dealing with this issue local climate assessment must be considered. With regard to the thermal environment in urban areas, it is important to include information on the incumbents' thermal comfort range and understand their sensations and preferences for certain thermal conditions.

Makaremi et al. (2012) also investigated people's satisfaction with their surroundings, this time in an educational campus in Malaysia; they identify a significant difference between local and international groups of students. Many of the local students declared the thermal conditions of outdoor environments acceptable, whereas most of the international students stated that the conditions were uncomfortable. Moreover, the Malaysian students greatly preferred humid conditions, unlike the international students who preferred the comfort of drier or slightly drier weather conditions. This endorses the different tolerance of people with a different background.

Thermal preferences can also take a different form, depending on the reason for venturing outdoors. Höppe (2002) summarizes the findings from a study on an Italian beach (Hoppe and Seidl, 1991); he also found that many vacationists exposed themselves voluntarily to objectively very adverse conditions higher than 40°C. This is due to the fact that beaches meet a particular set of thermal expectations where people had a mean thermal preference in the range of an expected thermal sensation between slightly warm and warm (de Freitas, 1985).

The RUROS project in Europe highlights the public awareness to the importance of outdoor spaces to fulfil the cultural, climatic and urban needs of their users and the environment. Findings by Nikolopoulou and Lykoudis (2006) on the importance of psychological adaptation through the 'perceived choice' (sometimes known as 'perceived control') highlights that individuals have over a source of discomfort, when visiting an open space. This can take a range of forms, from the choice of sitting to avoid discomfort, to being in the area voluntarily, not as part of one's duties. The difference between the last two is that people in the area who have chosen to expose themselves to certain conditions are more tolerant of the thermal environment simply because they can end this exposure by leaving, and need not depend on external factors (Zambrano et al., 2006; Nikolopoulou and Lykoudis, 2006).

The above studies present the idea of peoples' psychological preparation before they use the spaces. Designers must embrace the concept of the users' expectations of comfort, which serves to ease the creation of an optimum design method in extreme climatic conditions. The literature reviewed highlights the recommendation that field investigations should be conducted in each set of local conditions to understand the behavioural patterns of small groups of people. The findings from these should then be integrated in the design guidelines to enhance the quality of outdoor spaces. It is important to avoid errors by conducting structured unbiased surveys of a wide sample of users where subjective assessments could be very tricky.

2.3. Pedestrians' thermal transitions

2.3.1. The dynamic conditions

Where the physical and thermal environment changes incessantly or periodically, pedestrians experience spaces dynamically (Zhang, 2003). Therefore, two users who have experienced a series of spaces in the opposite sequence to one another may judge their conditions differently (Potvin, 2000). Previous studies have suggested that pedestrians' thermal comfort in any space is significantly influenced by the antecedent space (Chun and Tamura, 2005; Potvin, 2000). An individual's assessment of the microclimatic conditions in any space depends upon this own thermal state as an outcome of his previous exposure to a sequence of conditions and on the microclimate condition of his present location. For example, a sunny location with calm winds may be assessed as comfortable and pleasant by a person coming out of a shady street but the same spot may be considered too hot by someone entering from a sunny open space (Bruse, 2007).

Katavoutas et al. (2015) describes this as follows: 'thermal comfort under non-steady-state conditions primarily deals with rapid environmental transients and significant alterations of the meteorological

conditions, activity, or clothing pattern within the time scale of some minutes'. A study based on gathering the thermal comfort votes of pedestrians, along courses offering transient semi-outdoor (dynamic) conditions in transitional spaces states that "in real transitional spaces, people experience temperature change in the very short term and continuously, not once in 1 or 2 h like in the laboratory. There is no steady state when people are walking in transitional spaces" (Chun and Tamura, 2005).

Potvin (2000) highlights the need to bear in mind the dynamic nature of the thermal differentials to which a pedestrian is exposed when strolling in the city. His study discusses the importance of urban environmental diversity and transients. He illustrates (see Figure 9) that people moving from a space where the environmental conditions are moderate to a space where they are more intense feel a sensation of comfort is felt. If in successive steps or in a steep change the stimuli increases too much, the positive sensation wanes and becomes negative. An occupant is thus momentarily conscious of a positive change in his environmental conditions, followed by a neutral step where the comfort range is attained and then a change for the worse.

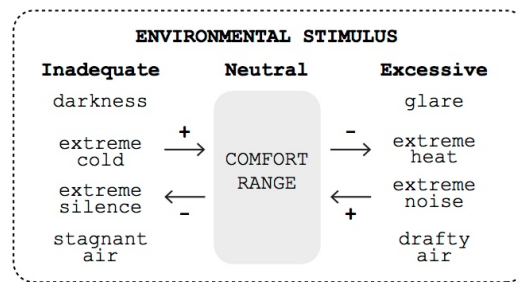


Figure 9 Environmental transition. Source: Potvin (2000)

Chen et al. (2011) traces the physiological process in such pedestrians. When the status of the thermal environment alters, human bodies acclimatize themselves by metabolic adjustment and thermoregulation to compensate for the change in heat transfer between the body core and the surroundings to maintain thermal balance. The excess body heat produced in response to the thermal loading of the environment results in an increase in the body core temperature, driving the thermoregulatory centre in the hypothalamus to transmit the body heat through the blood flow through tissues to the skin. Once it reaches the skin surface, the heat is dissipated via the vasodilation of blood vessels and subsequent perspiration, and the body gradually returns to a state of balance.

However, if the thermoreceptors sense a strong stimulus, such as that received in response to a sudden change in temperature, and call for a significant heat transfer, the thermoregulatory system may not effectively react to the cooling requirement. As a result, the thermoregulatory system may be overloaded and even disrupted. Hensen (1990), remarking that external thermal disturbances are

rapidly detected by thermoreceptors in the skin which enable the thermoregulatory system to act before the disturbances reach the body core, claims that it is important to note that the thermoreceptors in the skin respond to the temperature as well as to the rate of temperature change. According to (Madsen, 1984), they do this by sensing heat flow variations through the skin.

The successive changes of the thermal environment and the way that it influences one's thermoregulatory system depend on the temperature difference between two sequential spaces. This, known as the thermal distance, causes thermoregulatory changes, which reduce pedestrians' power to adapt. Chen et al. (2011) suggest that temperature differences between two spaces should be kept at 4°C or less to avoid an overshoot in the thermal sensation (Nakano, 2003; Potvin, 2000).

Chen et al. (2011) investigated people entering an air-conditioned thermal transition zone from outdoor spaces with a thermal status colder or warmer than that of the indoor thermal transient. He found that occupants working or living in the air-conditioned buildings constantly encounter a step change in air temperature when entering or leaving the buildings; on hot summer days, this change was sometimes considerable. This kind of drastic and instantaneous change in temperature can bring discomfort or even risk thermal stress, such as the risk of catching cold, to those who must regularly move across the temperature ramp. To cushion human bodies from the thermo-regulatory shock arising from sudden changes in the thermal environment, the temperature step in the thermal transition zone of a building, including its entrance area, foyer, atrium, lift lobby, etc., should be appropriately controlled. However, the experiments were conducted in a climatic chamber consisting of two adjacent rooms, each of which could be individually controlled for environmental variables, including air temperature, relative humidity, air velocity, and radiant heat.

It is also important to differentiate between pedestrians' comfort in a particular space – at a particular moment – and their overall comfort on the journey. For instance, pedestrians who were satisfied with their overall journey can still find it 'very uncomfortable' to be in a warm space, if interviewed. It has been observed, however, that most studies to investigate pedestrians' thermal comfort focus either on the relationship between two sequential spaces or on space 'snapshots'. Almost no studies conduct investigations on a continuous basis between nodal points of the urban area (Vasilikou and Nikolopoulou, 2014).

Vasilikou and Nikolopoulou (2014) argue that previous studies of thermal sensation and perception have tended to focus on the microclimatic conditions prevailing in a set of different spaces that may be in the same urban quarter or area, but are usually discontinuous, located in separate areas, or of a certain typology (Lenzholzer and Koh, 2010; Johansson, 2006; Ali Toudert, 2005). Sensory studies

often draw conclusions based on “sense walking” techniques. This consists of participants continuously walking and recording their sensory experiences usually, with regard to their visual, acoustic, and olfactory environment. However, the effect of thermal conditions and their variation on a pedestrian’s experience has not been investigated. This is mainly due to the complexity and multi-disciplinary nature of thermal comfort studies.

The way in which pedestrians experience the thermal environment outdoors is based largely on the sensory cues that they pick up in moving through in the urban continuum (Middleton, 2010). In their study, Vasilikou and Nikolopoulou (2013) investigate dynamic variations in thermal comfort as pedestrians move, in a comparative analysis of the thermal experience across a continuum of urban spaces. Their methodology includes sense-walking techniques and environmental and human monitoring. Their fieldwork is organized in structured walks where the participants walked along selected pedestrian routes in the centres of the two case study cities. Overall 314 questionnaires were completed to furnish their data. In Rome, the summer and winter thermal walks involved 90 interviews each, while in London 66 questionnaires were collected in summer and 68 in winter.

The study revealed a tendency for pedestrians to be able to perceive and identify consciously variations in the microclimatic conditions as they walk. Participants indeed seemed to associate climatic variables with specific urban spaces along their walking route. The findings also suggest that thermally-pleasant spaces do not share any specific geometric characteristics and may vary between seasons. The influence of visual perception as part of the overall satisfaction with the environment also was uncovered when the square that had vegetation and water features was voted in both seasons as that the most pleasant thermally.

Thermal walks employ a sense-walking technique that analyses the urban climate, the morphology of spaces and the way that people perceive their combined effect, through a series of structured walks with simultaneous environmental and human monitoring. This new process, introduced by (Vasilikou and Nikolopoulou, 2015, 2014, 2013), is based on point-to-point evaluations of thermal perceptions and spatial variations. Its special feature is the combination of objective microclimatic and spatial data with subjective responses by pedestrians on the street. The methodology was developed because of the need to understand how walking and moving between interconnected spaces may affect pedestrians’ thermal perception and thermal comfort. This comparative approach was initially developed for the analysis of visual perception and architectural studies (Cullen, 1961) and also for indoor thermal comfort studies (Givoni, 1976).

Using pedestrians as generators of data in the evaluation of outdoor thermal comfort is very important. Correctly interpreted, their contribution is vital and needs to be considered in the design of pedestrian networks identifying design improvements in spaces where people move or linger. The thermal representation of urban space may lead to significant results about projects aiming to encourage walkability and spatial quality in the everyday pedestrian environment.

2.3.2. Temperature step changes

In hot climates, it is common for pedestrians to experience significant 'steps' or changes within the thermal environment between one space and another. In Dubai, pedestrians register a thermal shock as they leave any building, due to the wide difference between temperatures indoors (air-conditioned) and outdoors, which can reach 20°C (Yannas, 2008). And as they walk along the mixes of sun and shade, they feel wide temperature differences due to the rise in the mean radiant temperature.

It is important to understand whether the step changes are moving towards or away from the comfort zone. In the course of a spatial transition, where participants were requested to express their thermal sensation vote (TSV) using a 7-point ASHRAE scale (3: cold; 2: cool; 1: slightly cool; 0: neutral, 1: slightly warm; 2: warm; 3: hot) and their thermal comfort vote (TCV) using a 6-point scale (3: very uncomfortable; 2: uncomfortable; 1: just uncomfortable; 0: neutral; 1: just comfortable; 2: comfortable; 3: very comfortable) (Zhang, 2003), people displayed a higher TCV when the temperature was moving towards what was comfortable. In contrast, if the transition made a comfort temperature more remote, we should expect a decrease in TCV (Wu and Mahdavi, 2014).

This finding is confirmed by those of Nakano (2003) and Chun and Tamura (2005). However, the findings of Wu and Mahdavi (2014) are based on evidence that involves only a very short walking distance. Nonetheless, it is conceivable that the activity level may have slightly increased during their respondents' transitions. The results also suggest that changes in people's thermal sensation votes (TSV) after a thermally relevant transition from one room to another are consistent with the difference between the temperatures of the two rooms.

Knudsen and Fanger (1990) investigated the impact of temperature step-changes on thermal comfort in a climate chamber. This study demonstrates that people are more sensitive to progressive cold than progressive warmth. Moreover, these writers highlight that the speed of adaptation to a new environment depends on whether the step change is directed away from or towards neutral conditions. The acceptability of the two step-changes away from neutral declines to below the steady-state level, and at least 20 minutes is needed before the votes attain this level once more. This contrasts with the step-changes towards neutral, where the steady-state level of acceptability is

reached within five minutes. In both cases, the immediacy of the thermal sensation response to temperature step-changes supports the hypothesis that it is the rate of change of the skin temperature rather than the skin temperature itself that is responsible for thermal sensation during fast thermal transients in the environment (Potvin, 2000).

Knudsen's conclusions suggest that it may be more important to prevent the sequence of spaces from becoming progressively colder, since this is more likely to trigger a behavioural response than if the sequence became progressively warmer. He explains that downward step changes (e.g., from warm to cool) trigger faster responses because the skin's cold receptors are closer to the skin's surface than its warm receptors. An extreme behavioural response, such as increasing the metabolic rate by faster movement, may have serious effects on the perception of space, social behaviour, and overall environmental satisfaction.

In the study of de Dear et al. (1993) study, the participants' thermal sensations did not overshoot when moving from a warm (T_a 35°C) to a cooler (T_a 24°C) environment, as suggested by (Kelly and Parsons, 2010), whose investigation yielded a larger temperature difference (i.e., 13 K, from 31°C to 18°C). Dahlan and Gital (2016) suggest that the thermal index Predicted Mean Vote (PMV) can be an acceptable alternative way of predicting thermal sensation immediately after a down-step thermal transition (from exposure lasting 1 min) among people living in a country with a hot-humid climate.

In general, discomfort is associated with any change in average body temperature, which applies to transient changes when the subject goes from comfortable to uncomfortable, neutral to cold, or neutral to warm. When these transients are reversed (i.e., cold to neutral, hot to neutral), the sensations of comfort and temperature “lead” the body temperature changes and are thus “anticipatory.” This hysteresis effect is felt most intensely in cold conditions and less in warm. For transients from cold to warm, the rate of rise in the skin temperature causes a sensation that compensates for and predominates over the sensation of discomfort caused by the original low skin temperature (Gagge et al., 1967).

Chun and Tamura (2005) name this tendency the “relative evaluation tendency” and verified it in field experiments. Where temperature variance makes an influence on thermal sensation, even though the temperature remains at 24°C, the placing of the temperature in the whole exposure and sequence of temperature conditions (i.e., whether it is part of a downward or upward process) influences the thermal sensation vote. If 24°C is a higher temperature in the temperature sequence, thermal sensation moves to a warmer evaluation. If 24°C is a lower temperature in the whole temperature pattern, the thermal sensation evaluates it as cooler.

It is recommended that future investigations should examine the possibility of reducing the temperature difference in conditions that promote the transient hysteresis-effect between air-conditioned indoor and warm outdoor conditions, in order to suggest more suitable indoor and semi-outdoor passive design strategies in countries with a hot-humid climate (Dahlan and Gital, 2016). It is believed that less noticeable hysteresis effects are partially a result of reduced thermal stress. Moreover, Dahlan and Gital (2016) have found that 20 min of exposure to an air-conditioned interior of 24°C can reduce the level of thermal comfort on returning to the humid warmth outdoors.

Chen and Ng (2011) monitored a person walking for 120 seconds in an urban environment. Findings reveal that pedestrians' thermal stress is quite high when the T_{sk} increases from 33.7°C to 34.8°C. In shade, the increase is not so high. The difference in the rate of change is consistent with the spatial variation of the T_{mrt} . However, the core temperature, T_{core} , changes much more slowly, increasing only by 0.18 °C after walking and is constantly 0.2 to 0.3 °C lower than the steady state. This suggests that in hot conditions, the core of the human body has a much slower adaptation rate than the skin has. The simulation result also shows that the thermal adaptation process of a pedestrian is dynamic, and the pedestrian never attains a static state, making some predictive tools that are based on static metabolic rates unsuitable to predict comfort. This will be discussed elaborately in section 2.4.

Potvin (2000) suggests that subliminal adaptation is a preferable explanation for what goes on when moving from a comfortable environment into a less comfortable one. In such cases, subliminal adaptation mitigates the marked sensation of discomfort that would need an important change to restore conditions to neutral. However, when moving from an uncomfortable to a more comfortable environment, an abrupt transition would appear acceptable. The possibilities of such environmental transitions are infinite and depend as much on the nature of a given climate as on the nature of built forms within it. Yet some general conclusions may be drawn: for example, passing from a wind protected and sunlit space to any other space creates on average 11.3°C equivalent temperature differential. It would therefore require more radical adaptive behaviour to overcome the transition. Passing from a wind-protected shaded or semi-shaded space to any other would create on average a 5.1°C equivalent temperature differential. This could easily be overcome by moderate adaptive behaviour. For other transitions, passing from a moderately windy and shaded, semi-shaded or fully sunlit space, or from an exposed and semi-shaded or fully sunlit space to any other, would create on average a 1.9°C equivalent temperature differential. This would barely be noticed and could therefore be described as subliminal.

2.3.3. Rate of thermal transition

The human body tends to adapt to successive slow changes. Makaremi et al. (2012) argue that people need some time in a space before they adapt to their conditions; they collected evidence from an educational campus in Malaysia to show that individuals who passed through the area for a short time had a lower tolerance for uncomfortable thermal conditions than those who came to sit or relax for a longer period, whose tolerance was high. The study showed that moving through an area quickly resulted in a low tolerance of uncomfortable conditions, whereas taking a little time to adapt built a higher tolerance. Pedestrians' levels of adaptation are a function not only of the climatic conditions but also of the levels of environmental diversity provided by different urban fabrics (Chun et al., 2004).

Potvin (2000) suggests that, to avoid discomfort and make walking an attractive option, the changes in people's thermal environment along a given path should be small enough to be subliminal. If in successive steps or in a steep change the stimuli increase too fast, positive sensations wane and become negative. An occupant is thus momentarily conscious of a positive change in his environment, followed by a neutral step where the comfort range is attained and then a negative change. The conditions in a space will therefore, as we have seen, be judged differently by two users if they experience the sequence in opposite directions, or walk at different speeds, the subjective judgements of environmental conditions being always affected by the preceding environmental condition or reference level.

When the environmental conditions change very slowly, below the threshold of sensation, the change may be subliminal. The body mechanisms tend to adapt to accommodate each successive change, making the subjective effect almost imperceptible. This phenomenon of adaptation occurs as the stimulus either increases or lessens. Thus, when thermal comfort demands environmental continuity, changes in the intensity of different environmental stimuli should be subliminal to avoid the sensation of discomfort. Kuno (2007) emphasizes that human physiological adaptation requires enough time for the body to adapt to such changes, whether the movement is between rooms or from indoors and outdoors. The time required depends upon many factors some of which are: the temperature difference between the two sequential spaces, the direction of temperature change and whether it is towards the comfort range or moving away from comfort, the physiological conditions of the person, other personal aspects such as their age and gender.

Later experiments by Wyon (1973) were designed to investigate the effects on the comfort and performance of pedestrians undergoing predetermined ambient temperature swings in more normal working conditions. From the results, these writers conclude: "Large temperature swings ... cause increased discomfort" and "Large ambient temperature swings appear to have a stimulation effect

that is to be preferred to the apparently opposite effect of small temperature swings, but a constant, optimally comfortable temperature, where this can be achieved, would still seem to be preferable to either". To be able to compare these results with those of other researchers, Wyon's raw data were examined. It was found that 80% of the votes were in the comfort zone for all swings with intended peak to peak amplitudes of 4°C or less. As indicated above, this suggests that the maximum acceptable peak to peak amplitudes of operative temperature fluctuation for the whole body is in the range 12°C.

Experiments with wide ambient temperature swings were also conducted by Nevins et al. (1975). Eighteen subjects of different ages were exposed to ambient temperature swings with a peak-to-peak amplitude of 10°C and an average fluctuation rate of 19°C. The mean ambient temperature was 25°C. From the results, it was concluded that the preferred ambient temperatures for comfort agreed well with the results of earlier steady-state experiments (on which, for instance, ASHRAE 55 is based) and that there was no clear evidence of fluctuation inducing an increased or reduced range of acceptable ambient temperatures. An examination of Nevins' raw data however suggests a maximum acceptable peak-to-peak amplitude of about 2.8°C. This is a little less than the width of the comfort zone for steady-state conditions. It should be noted that when unacceptable temperatures were left out, a rate of temperature change of 19 K would have resulted in a fluctuation frequency of about 3.4 cycles, or alternatively that 0.9 cycles would have resulted in an average rate of change of 5 K.

Rohles et al. (1980) conducted a series of experiments in which 804 subjects were exposed to cyclical changes around various basal temperatures (17.8 - 29.4°C) with different amplitudes (1.1 to 5.6°C). The results showed that if the (steady-state) temperature conditions for comfort are met, the thermal environment will be acceptable for near sedentary activity while wearing summer clothing, so long as the rate of change does not exceed 3.3°C and the peak-to-peak amplitude is equal to or less than 3.3°C (which is approximately the same as the width of the steady-state comfort zone).

From experiments in the 1950s by Hensel (Hensel, 1981), it is clear that when the human skin is exposed to changing temperatures the difference between a neutral temperature and a temperature at which sensations of warmth or cold occur (i.e. past the thermal sensation threshold) decreases inversely with the rate at which the temperature changes. This thermal sensation threshold depends also on the temperature to which the skin has adapted when the change starts, on the direction of change, on the exposed part of the body and on the area, being exposed. The latter two factors also have a considerable influence on the intensity of temperature sensation. Although it cannot be proved, these findings may well cause part of the contradictory results and conclusions of the experiments discussed above. The fact that there is a threshold for thermal sensations which is affected by the rate of temperature change suggests that the same is true for thermal comfort.

Probably because of the minor influence of moderate humidity on thermal comfort and thermal sensation, only a few experiments have reported the effect of changing humidity levels. Four studies, by Gonzalez and Gagge (1973), Nevins et al. (1975), Gonzalez and Berglund (1979) and Stolwijk (1979) indicate that when the operative temperature is within or near the comfort zone, fluctuations in humidity from 20% to 60% do not have an appreciable effect on the thermal comfort of sedentary or slightly active, normally clothed persons. Relative humidity becomes more important when conditions become warmer and thermoregulation depends more on evaporative heat loss.

2.4. Thermal sensation and thermal comfort

Thermal comfort was defined earlier in this chapter as the state of mind that expresses 'satisfaction' with the thermal environment. Satisfaction is a subjective and emotional experience, which varies between people (Hensel, 1981). Words such as "pleasant" and "comfortable", which are used to describe the state of comfort, do not have an absolute value, but are relative to experience and expectation (McIntyre and Griffiths, 1974), whereas thermal sensation is considered an objective experience, which describes a purely physiological condition in words such as "cold" and "warm". Hensel finds that temperature sensations (especially local cold sensations) depend mainly on the activity of thermoreceptors in the skin, whereas thermal comfort or discomfort reflects a general state of the thermoregulatory system (though this does not imply that changes in thermal comfort are always slower than changes in thermal sensation). The condition of thermal comfort is therefore sometimes defined as a state in which there are no driving impulses to correct the environment by behaviour (Fanger and Valbjorn, 1980).

According to McIntyre (1980), it is conventional to treat overall thermal discomfort (a subjective condition) in terms of thermal sensation. This may be justifiable in case of steady conditions, when people are at rest and the microclimatic conditions are stable. However, this does not apply to pedestrians, who are moving between different spaces. The difference between thermal comfort and a temperature sensation in changing environmental conditions is clearly demonstrated in experiments by Gagge et al. (1967). These researchers exposed subjects for one hour to neutral thermal conditions (29°C), then put them through a step change to a much colder (17.5°C) or warmer (48°C) environment for two hours of exposure, which was followed by a step back to neutral conditions.

On entering the cold conditions, the subjects immediately reported cold sensations and discomfort, which almost immediately disappeared on returning to the neutral environment, while temperature sensations lagged considerably behind the comfort reports and for some subjects did not return to neutral in the one-hour post-exposure period. Transient exposure to the hot environment elicited much the same responses. On entering the hot conditions, the subjects at once reported warm

sensations and discomfort. These feelings disappeared rapidly, though more slowly than in the case of the cold to neutral step, when they returned to the neutral conditions. The temperature sensations showed an overshoot with some initial reports of feeling slightly cool.

People take action to improve their comfort by 'adaptive' actions, for example, modifying their clothing and metabolic rate, or by interacting with the building (Nicol, 1990). Separating thermal sensation from thermal satisfaction, it was further demonstrated that 'adaptive opportunity' (the degree to which people can adapt to their environment) is important for their satisfaction with the space that they occupy. Conversely when adaptive opportunity is limited, a departure from neutrality causes stress and dissatisfaction (Baker and Standeven, 1996). This suggests that intrinsic factors such as past experience (Hawkes and Willey, 1977), naturalness (Griffiths et al., 1987) experience and expectations (de Dear, 1995), length of exposure (Baker, 1993), and the need for environmental stimulation (Baker and Standeven, 1996; Givoni, 1976) are also important for thermal satisfaction (Nikolopoulou et al., 2001).

To evaluate sensation, researchers often ask subjects to rate their perceptions using a 7-point ASHRAE voting scale that covers a range of warm and cool sensations, placing the mildest sensations (e.g., "slightly cool -1" and "slightly warm +1") near the centre of the scale. Researchers typically interpret all votes between -1 (slightly cool) and +1 (slightly warm) as "comfortable." This is the basis of Fanger's (Fanger, 1970) PPD (Predicted Percentage of Dissatisfied) model, which is based on an actual Predicted Mean Vote PMV (Zhang, 2003). Another way to evaluate thermal comfort is to ask the subjects' thermal preferences: 'I would prefer to be warmer', 'I would prefer to be colder', 'I would prefer no change'. Preferring no change is considered to represent "comfortable", or perhaps more precisely, "ideal".

The comfort zone specified in ASHRAE Standard 55-1992 is based on 90 percent acceptance by subjects of thermal conditions (or 10 percent dissatisfaction) (Brager and de Dear, 2001), based on the whole body/heat balance. It assumes that another 10 percent would simultaneously be dissatisfied due to local discomfort. Fanger (1970) relates the predicted percent who are dissatisfied (PPD) to the predicted mean vote (PMV) and defines dissatisfaction as any vote other than -1, 0, +1. The PMV model and PPD model are the bases of ISO Standard 7730 (ISO 7730, 2005).

Brager and de Dear (2001) challenged the ASHRAE standard by proposing an adaptive comfort standard and broadened the findings from field studies that the range of thermal comfort in naturally ventilated buildings is much wider than the ASHRAE standard indicates. The adaptive standard is

based on subjects' "preferences rather than the traditional assumption that "neutral thermal sensation" is the optimum thermal condition.

2.5. Uniform and non-uniform environments

The relationship between thermal sensation and thermal comfort was first investigated by Gagge et al. (1967), who collected and analysed human responses to various environments with temperatures ranging from 12 to 48°C. The study introduced the uniform environment, which represented the thermal condition of a physical space. In a uniform environment, it is assumed that the heat sources are distributed evenly over the various parts of the body, giving the same effect and resulting in an overall thermal sensation or comfort level. The thermal environment of the human body is a symmetrical homogenous environment, which is usually the condition assumed by all existing thermal comfort prediction models (Zhang, 2003; Rohles et al., 1980; Nevins et al., 1975; Fanger, 1970; Schlegel and McNall, 1968). This is understandable, since the number of variables is not fixed and affects the results.

However, this does not mean that we perceive a uniform environment as more comfortable. Several former studies (Attia and Engel, 1981; Mower, 1976; Cabanac, 1971) (Mower, 1976) tested people's pleasure when cold and warm thermal stimuli were applied to the hand, forehead, and neck. Their tests demonstrate that subjects in a hypothermic state experienced pleasure when warm sensations were felt in these areas, while subjects in a hyperthermic state experienced pleasure when cold was applied to these areas. In short, a varied thermal environment appears to be experienced as more pleasant than a uniform one. This is discussed further in section 2.7, which describes the influence of locally cooling certain body parts as a way of improving thermal comfort.

Zhang (2003) asserts that in thermally asymmetrical environments, we cannot evaluate thermal comfort using neutral thermal sensations (votes within +1 and -1 on the ASHRAE thermal sensation scale) because different body parts may feel comfortable in the context of conditions that the rest of the body is experiencing. For example, a warm hand will probably be perceived as pleasant when the whole body is cold, and vice versa. Cabanac (1971) put human subjects in baths with water temperatures of 23°, 28°, 33°, 38°, and 40° C; while in these baths, the subjects put their hands in a glove containing water whose temperature the subject could adjust according to preference. The authors found that subjects preferred warm glove temperatures when their internal temperatures were cold (hypothermic) and cold glove temperatures when their internal temperatures were warm (hyperthermia).

Zhang (2003) proposed an overall thermal comfort model for non-uniform and dynamic conditions based on the human response of local thermal comfort, which is related to local thermal sensation and overall thermal sensation. Results indicated that the non-uniformity of the thermal sensation affected thermal comfort significantly in non-uniform conditions, depending on the intensity of the stimuli and the body part being affected.

Human responses to non-uniform and dynamic environments are different from the responses to uniform and steady environments and the proper assessment of the thermal environment is the basis for well-designed non-uniform or non-steady environments (Zhang and Zhao, 2008). Because the relationship between sensation and comfort is very different in transient and asymmetrical environments from that in uniform, stable conditions, the designer needs to know about both sensation and comfort in order to predict what they will require in transient, asymmetrical conditions. Both skin temperature covering local body parts and core temperatures must be measured in order to develop detailed sensation and comfort models. No experimental data have so far been available for this purpose. The study of human subjects in asymmetrical and transient conditions must be designed to fill this gap in the experimental literature. Hence, it is very difficult to predict pedestrians' dynamic conditions of thermal comfort in an outdoor environment (which is always non-uniform).

2.6. Predicting pedestrians' thermal comfort

A study (Chen and Ng, 2011) that summarized the methods of assessing thermal comfort outdoors divided them into two parts: steady-state and non-steady-state methods. The former are biometeorological indices developed to describe human thermal comfort levels by linking local microclimatic conditions and human thermal sensations (Task Committee on Outdoor Human Comfort of the Aerodynamics, 2004). These models assume that people's exposure to an ambient climatic environment has, over time, enabled them to reach thermal equilibrium providing numerical solutions to the energy balance equations that govern thermoregulation.

Most of the established models are empirical in nature and consider heat exchange and comfort as static. Such dynamics allow these models to provide accurate predictions indoors. However, the problem with this method is that it cannot effectively account for the dynamic aspects of the course of human thermal adaptation such as that pedestrians experience. This means, that in indoor conditions the indices based on steady state models are appropriate for thermal comfort assessments, whereas in the relative short time spent outdoors, mostly less than an hour at a time, a thermal steady state is hardly ever reached (Höppe, 2002).

An investigation was conducted by Höppe in 1989, using model calculations with the Instationary Munich Energy-Balance Model (IMEM). Two scenarios of different conditions were compared. The first was of a cold winter day (0°C , 5hPa and 1.0m/s) and the second was of hot conditions (30°C , 15hPa and 0.5m/s). In both scenarios, the model subject, coming from a thermal indoor climate close to neutral with a mean skin temperature of 33.5°C and a body core temperature of 37.0°C , left the comfortable house, wearing a coat of 1.5 clo and walked slowly to a work metabolism of 100W. Changes in the Tsk were substantially different in the two scenarios; it takes a long time in cold conditions to get close to steady state levels. The steady state level referred to indicates an adaptation of the body whereby the thermoregulatory process reaches a balance. A drop of 5.9 K (from 33.5°C to $27.3^{\circ}\text{C} \pm$) in the Tsk was achieved after a drop indicating the retarded influence of the cold environment on body core temperature.

However, in hot conditions, after 1 h of outdoor exposure, Tcore was at a value of 36.8°C , just 0.2 K below the starting level. Even after 3 hours, Tcore had declined only to 36.7°C , still 0.8 K above steady state level 35.9°C . The theoretical thermal steady state i.e. the Tcore does not change more than 0.01 K/h, is reached after 43 h of outdoor exposure representing 26 h if the steady state definition is based on a 0.1 K range. This means that in real life conditions, the thermal steady state is never reached even when people have spent several hours outdoors. Steady state comfort models, therefore, cannot provide realistic assessments in these conditions.

In fact, Nikolopoulou et al. (2001) agrees that the steady-state models will cause problems if applied in outdoor pedestrian thermal comfort assessment because they are based on a uniform metabolic rate throughout the walking journey. While in reality, a person metabolic rate probably increases from the second they start walking onwards. Indices such as PMV, OUT-SET and PET are all based on steady-state models, meaning that the resulting values indicate the thermal comfort condition of the subject after she/he has reached thermal equilibrium. For pedestrians outdoors, this pre-assumed state is hardly ever achieved, because walking involves transient processes and constant dynamic and temporary thermal adaptation. In this case, the use of steady state indices will normally cause problems in assessing pedestrians' "actual" thermal sensation.

The findings of de Dear and Potter (2000) argued that the perception of outdoor thermal sensation is different from that indoors; postulating that "indoor thermal comfort standards are not applicable to outdoor settings". They find that according to the steady state model they used named the Predicted Mean Vote (PMV), holiday-makers can be predicted to reach thermal neutrality at 24.1°C . However, field observation in the outdoor spaces that they studied revealed a largely different value of 27°C . This does not only confirm that such index should not be used for outdoor prediction of comfort, but

also the importance of field measurement and observations to validate the predicted values of comfort when dealing with the outdoors.

Indeed Höppe (2002) has explicitly demonstrated the difference between a pedestrian's dynamic thermal adaptation and the theoretical steady state condition, using a simple "sunny street segment" case

Figure 10. He shows that there are many specific situations in which even in hot conditions steady state is widely irrelevant. An example of such a situation might be a simulation of a pedestrian coming out of the shaded area of a sidewalk and entering a 200 m long sunny segment. The simulation involves an air temperature of 30° C, air velocity of 0.5 m/s and mean radiant temperature of 25° C for the shady segment and 60° C for the sunny one. The walking speed is 4 km/h which results in an exposure to the sunny conditions that lasts 180 s. Steady state measurements of Tsk and Tcore are reached quite quickly, after 28 min and 56 min for Tsk and Tcore respectively. From the sixth minute onwards, there is a kind of overshoot of mean skin temperature with slightly higher values than in there would be in steady state. This can be explained by the lag of the onset of sweating, which at this stage is not yet fully efficient. The results of these calculations for heat stress imply that steady state thermal comfort models can provide sufficient information for persons staying outdoors for more than half an hour.

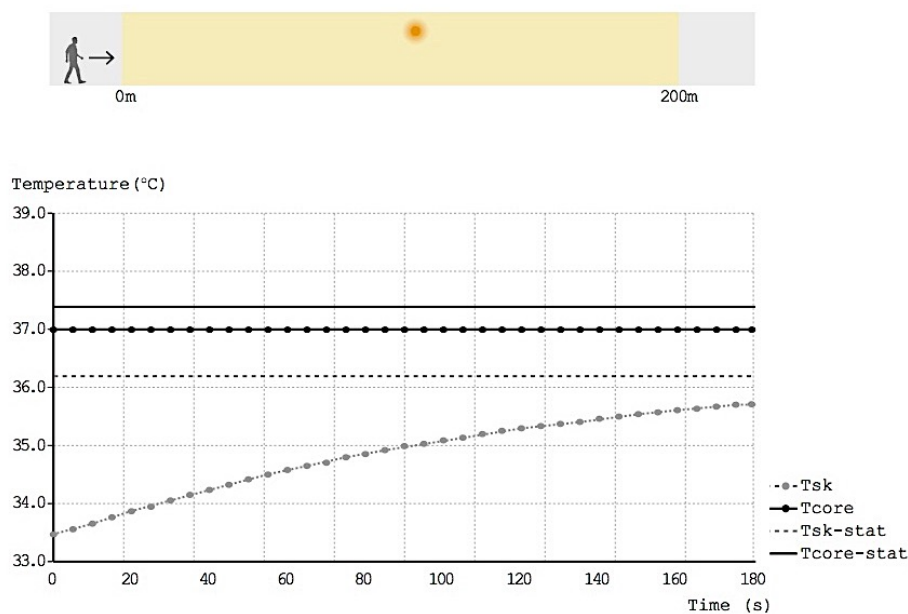


Figure 10 Difference between a pedestrian's dynamic thermal adaptation and the steady state condition: (a) scenario "sunny street segment"; (b) temporal variation of pedestrian's physiological conditions, described by skin temperature (Tsk) and core (Tcore). Tsk-stat and Tcore-stat are steady state skin temperature and core temperature, respectively. Source: Höppe (2002)

If assessed by the steady state models, the sunny segment would be characterized by PMV 3 (hot) or Tsk 36°C and Tcore 37°C. After 180s, Tsk reaches 35.8°C, which is already quite close to steady state, but Tcore is still 37.0°C, which still means no change at all. Someone experiencing these changes in body temperatures probably would have a thermal sensation of heat but would certainly encounter no health risks. A scenario like the one discussed here is quite typical of the questions that urban planners put to urban bio-climatologists if the former want to know whether it is wholly necessary to change the conditions in such a street canyon to encourage walkability.

The dominant lack of thermal comfort indices developed and validated for outdoor environments justifies the inaccurate use of static indices in many studies that focused on outdoor comfort. However, these studies conducted fieldwork measurements and comparative analysis between predicted and actual values, which helped researcher and climatologists develop them further. An example of that is a steady-state model index that has been widely applied in areas with various climatic conditions (Cheng et al., 2012; Lin et al., 2010; Sofia Thorsson et al., 2007; Ali-Toudert and Mayer, 2005) named the Physiological Equivalent Temperature (PET) (Mayer and Hoppe, 1987). This index has been modified later in 2014 by Chen and Matzarakis (2014) and presented as mPET. The modified version is more sensible to the metabolic rate and clothing values, which gives it higher accuracy to determine dynamic comfort conditions. However, the modified index (mPET) remains to function on the same principles as the former one (PET). Since it's a new index and has not been used widely, therefore, few studies that discussed PET will be reviewed below to understand it's principles, which will also be used comparatively at a later stage of this research.

PET is a temperature dimension index measured in degrees Celsius (C), making its interpretation comprehensible even to people who know little about meteorology. It translates the evaluation of a complex outdoor climatic environment to a simple indoor scenario on a physiologically equivalent basis that can be easily understood and interpreted, which allowed many researchers to use it in predicting outdoor comfort. The index is based on the Munich Energy-balance Model for Individuals (MEMI) (Hoppe, 1984) and is defined as the air temperature at which, in a typical indoor setting, the human energy budget is maintained by the skin temperature, core temperature and sweat rate equal to those under the conditions to be assessed (Hoppe, 1993). The repeated usage of PET in a wide number of studies including large scale projects such as RUROS and KLIMES had validated its suitability in multiple climatic conditions.

Matzarakis and Mayer (1996) assert the need for special investigations in various climates worldwide to validate the thermal sensation ranges given by PET shown in Table 1. These numbers were derived from analogous PMV ranges (VDI 1998) that are based on investigations by Fanger (1970). The ranges

of PET depend on the internal heat production that is assumed and the thermal resistance of clothing. They argue that the ranges for PMV and PET may move to higher or lower as our perception of the thermal environment or physiological processes changes and we adapt accordingly. Other researchers have tested these ranges and found some discrepancies where the comfort range in a particular climate may not be applicable to that in another region (Lin et al., 2010).

Table 1 Ranges of PMV and PET for different grades of thermal perception and physiological stress.
Source: Matzarakis and Mayer (1996).

PMV (°C)	PET	Thermal perception	Grade of physiological stress
-3.5	4	Very cold	Extreme cold stress
-2.5	8	Cold	Strong cold stress
-1.5	13	Cool	Moderate cold stress
-0.5	18	Slightly cool	Slight cold stress
0.5	23	Comfortable	No thermal stress
1.5	29	Slightly warm	Slight heat stress
2.5	35	Warm	Moderate heat stress
3.5	41	Hot	Strong heat stress
		Very hot	Extreme heat stress

A study from Taiwan verifies the accuracy of the RAYMAN model, which uses PET to calculate comfort, in predicting people's comfort in outdoor spaces (Lin et al., 2010). The Taiwanese people were shown to be more tolerant of hot air temperatures than are Europeans residing in temperate regions. For example, a Taiwanese person may feel "cold" when $PET < 18^{\circ}\text{C}$, whereas a European may feel "cold" only when $PET < 8^{\circ}\text{C}$. Such finding suggested that outdoor spaces in Taiwan must be planned to avoid an excessively low sky view factor (SVF), which creates more shade, thus making people feel cold and contributing to thermal discomfort in winter. The results indicate the accuracy of RAYMAN's prediction of long-term thermal comfort where the values were similar to those measured. The ranges suggested by this study and presented in Table 1, remains the most reliable to have been devised for outdoor studies and hence, is used in the present study to compare people's predicted comfort ranges compared to the actual votes. Besides, the thermal perception values presented in Table 1 were very similar to the actual thermal sensation votes of pedestrians in Dubai gathered during pilot investigations. Therefore, researchers should always compare actual votes from fieldwork with those predicted from indices for validation, not only between different regions, but, also between different areas.

In Malaysia, the findings of field measurements showed that the values of PET in the selected shaded outdoor spaces of an educational campus were higher than the comfort range defined for the previous

study of reactions to a tropical climate shown in Table 2 (PET < 30°C). Nevertheless, acceptable conditions (PET < 34°C) normally occurred at a relatively early time of day (9-10 am) and in late afternoon (4-5 pm), while the locations with a high degree of shading from plants and surrounding buildings had a longer period of thermal acceptability (Makaremi et al., 2012). Therefore, it is possible that a slight discrepancy remains valid under various conditions, although no index that is applicable worldwide has so far been developed.

Thermal sensation	PET range for Taiwan ^a (°C PET)	PET range for Western /middle European ^b (°C PET)
Very cold	<14	<4
Cold	14–18	4–8
Cool	18–22	8–13
Slightly cool	22–26	13–18
Neutral	26–30	18–23
Slightly warm	30–34	23–29
Warm	34–38	29–35
Hot	38–42	35–41
Very hot	<42	<41

Table 2 Thermal sensation classification for Taiwan and Western/Middle European
Source: Makaremi et al. (2012)

PET has been used in Riyadh, a hot city within the gulf region with similar lifestyle characteristics. Abdel-Ghany et al. (2013) has revealed that between April and November most people feel hot almost all day (9:30-5:00) Figure 11. The air temperature was found to be between 34°C and 40°C. In the morning and at night, when the air temperature is between 29°C and 33°C, the thermal sensation ranges between slightly warm, warm and hot, irrespective of clothing and activity level. The authors argue that increasing the level of activity provides a higher thermal comfort level from increased sweating and respiration rates. This is slightly different than studies conducted in Dubai, which reveal that pedestrians are at lower levels of heat stress than those shown in Figure 11 (Balakrishnan, 2012; Thapar, 2007). This is due to the hot and dry climatic conditions of the city of Riyadh compared to the hot and humid conditions of Dubai. Such thermal perception predictions may in fact be restricted to the geographical area, or type of climate where the field survey was conducted (Johansson et al., 2014). Therefore, comfort indices should be tested and calibrated on actual samples of people when linked to a different climate than the one in which they were developed.

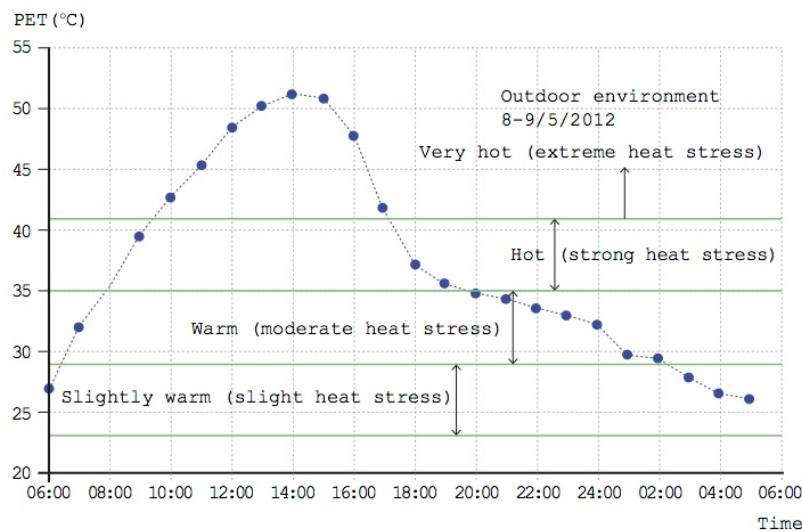


Figure 11 Time course of the physiological effective temperature (PET) estimated outdoors on a hot summer day in the central region of Riyadh. Source: Abdel-Ghany et al. (2013)

In 2014, a significant update of the microclimatic simulation tool ENVI-met (Bruse 2004) was released, incorporating the index PET to calculate thermal comfort. Generally, the software is used to – but not limited to – calculate numerous outdoor parameters on a three-dimensional level at specific points and locations within an outdoor space aiming to read the microclimatic influence of built forms and landscape. Now the tool has become considerably helpful to researchers, as it could be appointed to predict the influence of the built environment on thermal comfort. This is deemed an imperative enhancement to an outdoor simulation tools that is widely used and validated through many studies. Therefore, PET is used in this study to predict the influence of the built environment on thermal comfort through ENVI-met, with the privilege of altering multiple scenarios.

Variations in air humidity and clothing insulation is adjusted in the modified PET index (mPET) (Chen and Matzarakis, 2014) on thermo-physiological mechanisms and clothing factors for universal application in all climate zones. The physiological thermoregulation of mPET is adapted to a simple multi-segment body model including a blood pool element and a bio-heat transfer principle, instead of the two-node human body model used in PET. A multi-layer clothing model with clothing insulation and vapour resistance is established for mPET. It replaces the single-layer clothing model applied in PET. With these two modifications, mPET can evaluate thermal conditions influenced by vapour pressure and clothing insulation (Chen and Matzarakis, 2014). The study tested the sensitivity of the index to various microclimatic parameters such as T_a , MRT, RH and V and, most important, the clothing value, which proved to give it greater accuracy than PET provide. Therefore, mPET was judged to be a useful and reliable thermal index for universal application (Chen and Matzarakis, 2014). However, mPET being a newly released index has not allowed its expansion in many studies and

incorporation in tools such as ENVI-met. Hence, both indices (PET and mPET) are used in this study and compared to the actual votes of comforts gathered from field surveys.

Another strategy developed by Olgyay (1963) helped urban designers to take maximum advantage of the climate and predict the comfort conditions at different seasons by changing some parameters, such as wind speed and the degrees of shade. It is one of the oldest tools to have been developed on the basis of a relationship between environmental parameters and thermal comfort, namely, The Psychrometric chart, derived from the original bioclimatic chart developed by Olgyay (1963), set out in a Cartesian format. The charts show the four dominant environmental parameters (air temperature, humidity, air motion and radiation) for a person wearing his/her usual indoor clothing of average 1.0 clo and with a slightly active 1.3 met on average (as with office work).

This tool was used by Balakrishnan (2012) to analyse the climate of Sharjah, a city within the U.A.E. of comparable climate to Dubai's, from Meteonorm 6.1, using the weather cycles presented by Yannas (2008) the Psychrometric chart to plot pedestrians' comfort limits. This climatic classification is also used in the present study, where the tests conducted by Balakrishnan provided an initial understanding of the influence on thermal comfort of different wind velocities and degrees of shade (Figure 12). The Psychrometric chart plotted for a clo value of 0.4 (summer clothing) and a 1.3 met, which represented quasi-sedentary activity such as slow walking. The MRT was assumed to be equal to the air temperature. The comfort limit was set for summer periods and outdoor spaces, where the air velocity and radiation levels were above the indoor average.

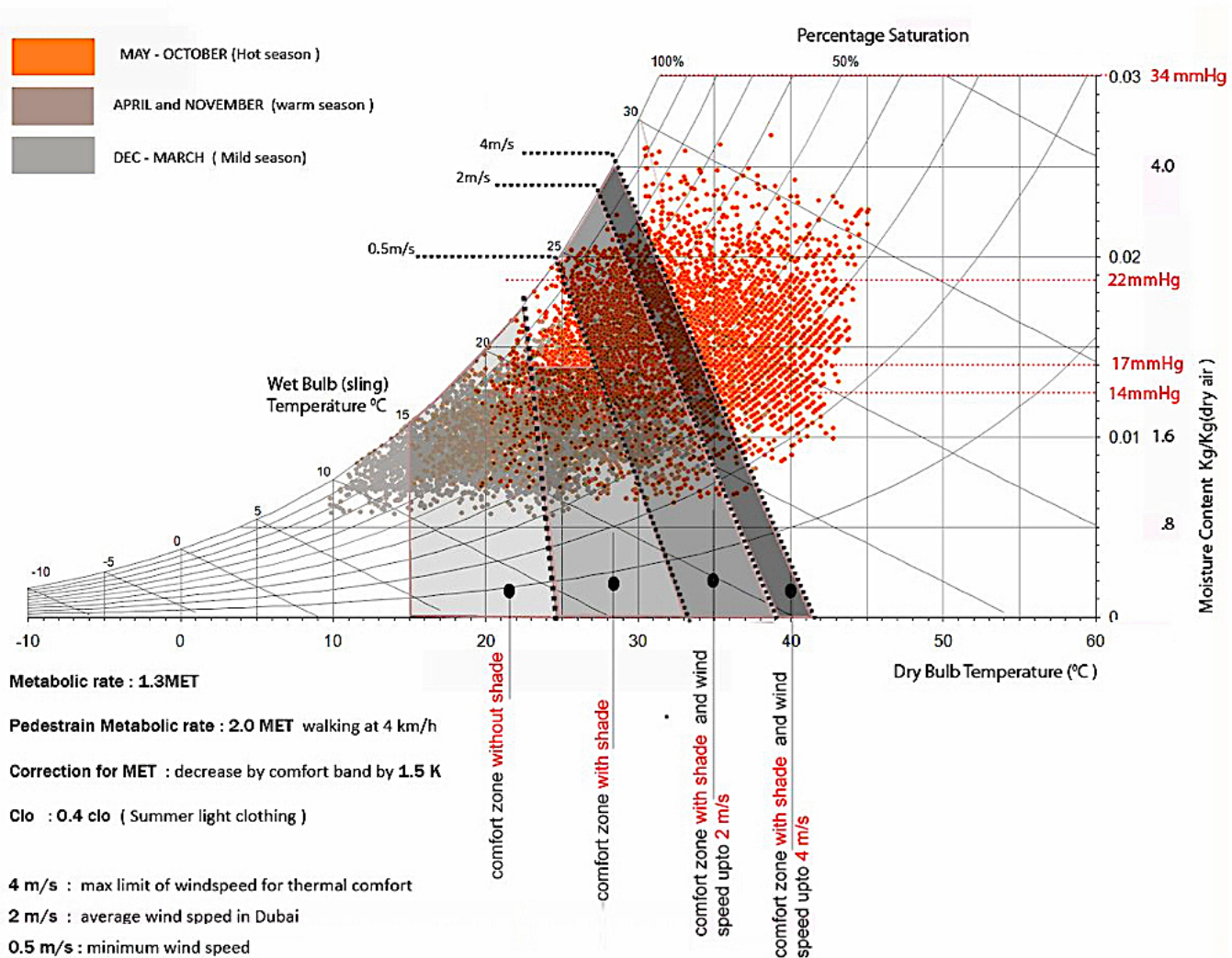


Figure 12 Psychrometric chart with extended limits for summer comfort in outdoor spaces. Source: Balakrishnan (2012)

The different shades of grey shown in Figure 12, highlights the comfort band at various shading and wind conditions. The chart demonstrates a Dry Bulb Temperature range for comfort between 15° - 25° C without any external shade or shading canopy, 25° to 32° C in shade and still air conditions, which can be extended to 39° C if wind accelerates to 2m/s. This limit conforms to the findings of the fieldwork survey conducted by Thapar (2007) in Dubai, which concluded that people found ambient temperatures close to 40°C acceptable when there was shade and to wind velocities of 2m/s. This tool even helped test higher air velocities to identify the optimum value, at which the air motion produces the highest cooling. This value should not be too low to allow the evaporative cooling on the skin to occur and not high enough to allow convective exchange to warm the body (Givoni, 1976). Balakrishnan suggests that in the hot period (at 40°C) the optimum wind speed required for sedentary

activity averages between 1.2 and 2.0 m/s (for 1.2 -1.4 Met) and for a pedestrian walking the optimum velocities average between 2.9 and 4 m/s. It can be concluded that in the hottest periods in Sharjah, air velocities up to 4m/s have a positive impact for thermal comfort. Such predictions, are considered very informative for many researches investigating thermal comfort this climate.

There are other types of models that have been developed to predict thermal comfort in dynamic conditions. For example, PedNaTAS (Chen and Ng, 2011), BOT-World (Bruse, 2007) and IMEM (Katavoutas et al., 2015). As dynamic models require a large amount of fieldwork, tools, and involve a larger number of environmental parameters therefore, none of these models were developed enough and validated for global use. These models have been based on few number of individuals, they are also able to simulate different human characteristics, such as age, weight or climatic adaptation, which is beyond the capacity of static state indexes. In order to be practically applicable, individually-based models require a computational framework which simulates the movement patterns of the originals though an urban environment and provides the bio-meteorological models with the required microclimate data as input. One elegant way to construct such a system is to link the individually-based thermal comfort model to a Multi-Agent Simulation system (MAS). With a link of this kind, software agents take on the role of virtual humans moving through the model environment and different microclimate conditions while their thermal comfort is constantly monitored. The lack of such models remains a challenge for researchers aiming to investigate pedestrians' outdoor thermal comfort (Bruse, 2007).

In the KLIMES project, the Environmental Modelling Group (EMG) of the Johannes Gutenberg University of Mainz modelled four quarters in the city of Freiburg with the three dimensional microclimate simulation ENVI-met (Bruse and Fler, 1998) and used these results for a dynamic simulation of human thermal comfort with the MAS BOT-World (Bruse, 2009). Simulations with BOT-World show that a clever distribution of shady places throughout a quarter can effectively lower thermal heat stress for pedestrians, even if their route includes passages with high radiative temperatures and PET values (Huttner et al., 2009).

The MAS BOT-World was developed to simulate and analyse pedestrian movement and thermal comfort in complex urban environments. The simulation system integrates the bio-meteorological thermal comfort model ITCM and the pedestrian traffic simulation model PedWalk. The required microscale meteorological data are taken from ENVI-met simulations. In an MAS simulation, the climatic data are provided as boundary conditions for the ITC model (Bruse, 2007). However, the main limitation of BOT-World, apart from its sparse documentation, is its monotonous rasterized representation of the urban environment; it lacks high level of urban context, such as the buildings

and street networks that could carry socio-economic information. Furthermore, BOT-World is not developed in a GIS framework, so it might be difficult to apply worldwide. A simulation system with a comprehensive urban context and GIS-support is yet to be developed (Bruse, 2007).

As the agents walk through the domain, they are exposed to different virtual microclimates. The impact of these climatic environments on an individual's thermal comfort is simulated using a dynamic model of the human thermoregulatory system. A Fuzzy-Logic-based rule system is used to assess the local microclimate, taking into account not only its climatic conditions but also the thermal state of the agent. Depending on their individual thermal comfort level, the agents can adjust their routing decisions and also consider using optional facilities such as benches or restaurant chairs. MAS makes it possible to analyse the impact of such dynamically changing conditions on the thermal state of the simulated pedestrian and to make assumptions about the resulting usage patterns of urban open spaces (Bruse, 2007).

However, while the bio-meteorological model of the human thermoregulatory system is physically based, the rules used for the behaviour simulations are not. Therefore, they must be calibrated to the specific situation in order to produce realistic results. Hence, the simulated usage patterns should be interpreted as prediction maps of potential frequentation rather than specific pedestrian counts. The application of a MAS such as BOT-World to analyse a situation should be seen as "play" with different scenarios, as in a Decision Support System. The outcomes are based on some general assumptions about the way in which the design options can influence human behaviour. These results are only as good as the implemented rules are.

Nevertheless, conclusions on the best strategy for a successful urban design are based on general rules of thumb and basic assumptions of the experts and urban planners ought to make decisions. The final decisions are always based on personal experience that might be limited to a certain location or conditions and might not be suitably applicable elsewhere. Many misconceptions are usually made to overcome the lack of the large amount of fieldwork required to verify the strategies suggested, which might not be feasible or efficient at that moment. Besides, the assumptions made are usually more subjective and disputable than the outcomes given by a computer assessment system that is run based upon a certain context and conditions. Therefore, the outcomes and findings should be strictly limited to those situations where general assumptions are extensively defined and justified to ensure the neutrality of the data analysis process. There is a need for reliable simulation tools that could be adequately used to overcome such problem.

Chen and Ng (2011) emphasised the need to develop a methodology for integrating a microclimate assessment with pedestrian behaviour modelling in a comprehensive framework. These two writers developed a system which has functions of pedestrian simulation and urban climate modelling implemented with GIS support. Through a simple proof-of-concept case study, they illustrate how the system can be used in the real world but again, did not develop it further.

The PedNaTAS system is an agent-based integrated decision support system that assesses pedestrian thermal comfort. It is an agent-based simulation system working at three levels to model a typical pedestrian's walking behaviours: social, proactive and reactive behaviours. The social behaviour modelling takes a simple activity-based approach, using the discrete model to estimate the probability of an exit point being selected as destination. Proactive behaviour modelling is essentially route-planning based on origin and destination. The reactive behaviour modelling deals with pedestrians' timely displacement, how they avoid static obstacles such as buildings, how they detect potential collision with other pedestrians and avoid it and how they occupy space on sidewalks and car routes.

The thermal comfort assessment module evaluates pedestrians' thermal sensations as they walk in the urban environment. Pedestrians' thermal sensation is determined by the local climatic condition of their changing surroundings, described in terms of air temperature, solar radiation, humidity and wind speed and their individual characteristics such as body weight and walking speed. This module provides both steady-state and dynamic assessments. The steady state assessment calculates the standard PET index of a particular person and generates the spatial variation of PET as a reference for analysis. The dynamic assessment uses the Pierce Two-Node Model (Gagge et al., 1971) which has been widely adapted in thermal comfort studies to monitor the temporal course of a pedestrian's thermal condition, including skin temperature, core temperature, etc. in walking. Because of the individual base of the system's approach, detailed conditions for any pedestrian can be examined, visualized and analysed. These individual thermal conditions could be linked with the global emerging pattern of the walking activity and provide implications for the use of space use.

Chen and Ng (2011) argue that town planners and decision makers, when faced with the task of designing urban spaces that are desirable and thus used rather than abandoned, will be better informed if they have a predicting tool that allows various design alternatives to be compared and tested for attractiveness and effectiveness. They suggest that a testing tool is needed that can provide both quantitative and qualitative understanding of the inter-relationships among microclimatic environment, subjective thermal assessment and social behaviour. Such a tool should be able to process detailed environmental information according to time and location variations and to generate analytical results to reveal relationships.

2.7. Improving thermal comfort

2.7.1. Solar protection and heat stress relief

Zhang (2003) described a very old and simple experiment by the English philosopher John Locke in his 1690 'Essay Concerning Human Understanding'. A person places one hand in a basin of warm water and the other in a basin of cool water. After a short time, both hands are placed together in a third basin of water, which is at an intermediate temperature. The hand previously in warm water feels cool and the hand previously in cool water feels warm even though they are at the same temperature. This corresponds with the belief that thermal pleasure is associated with the partial relief of thermal discomfort. When a body's heat stress is eliminated, maximum comfort is experienced – in other words, subjects feel a stronger sense of comfort in this transient, asymmetrical thermal state than under uniform, stable, neutral conditions. Kuno (2007) suggests that deliberately inducing and then easing thermal stress produces maximum thermal comfort.

This is not far from what pedestrian's experience in hot climates after walking outdoors for a few minutes and then moving to an air-conditioned indoor space. The instant improvement in thermal comfort that they experience is mainly due to the heat stress relief. This is due to the large thermal distance between outdoor and indoor temperatures where the step transition is downwards, towards the comfort range. This is also felt when subjects move from a non-shaded to a shaded space. The shift allows pedestrians to experience instant heat stress relief, which has been found to instantly boost thermal comfort but not thermal sensation. The delay between changes in the thermal comfort and the thermal sensation discussed above in this chapter play a great role here. Where the psychological impact of expectation is involved, people perceive shaded space to be cooler, which does not necessarily be the case due to the influence of the MRT. Local sunny or shady conditions significantly influence people's desire to stay or to leave (Gehl, 2010). Therefore, as people move to the shade they feel more comfortable even when the thermal parameters of the space are not much cooler.

This highlights the importance of shaded sequential spaces for influencing people's satisfaction and presence outdoors (Lin et al., 2012; Eliasson et al., 2007). However, beyond the physiological consequences of shade, several researchers have observed that people living in a specific climate have different perceptions of the effect of shade on thermal comfort, depending on their expectations (Villadiego and Velay-Dabat, 2014; Lin and Matzarakis, 2008; Nikolopoulou and Steemers, 2003). Studies conducted in a temperate climate conclude that, in winter and summer alike, the higher the solar access, the higher the attendance of an open space (Eliasson et al., 2007; Thorsson et al., 2004). Conversely, levels of attendance in warmer regions are heavily reduced when shade is not provided.

Cohen et al. (2013), Nikolopoulou and Lykoudis (2007), Lin et al. (2011 and 2010) and Watanabe et al. (2014) underline the high use of shaded locations in summer for Mediterranean urban areas in Tel Aviv and Athens and in tropical urban areas in Taiwan and Nagoya, Japan. A direct comparison between the attendance of open spaces in Japan and Sweden confirms this (S. Thorsson et al., 2007). People from these two countries expressed dissimilar attitudes to shade: more Japanese people than Swedish seek shade when air temperatures are higher than 20°C, while sunbathing is a very common activity in Sweden, but is extremely rare in Japan (0.2 % of people in a park, 0.6 % of people in a square).

The critical role of shade for human thermal comfort can be directly promoted by urban design. In fact, for a given open space, shade is determined by sun position, orientation and urban morphology, namely, the shape and position of buildings and vegetation (Klemm et al., 2015). Therefore, the importance of shade for improving pedestrians' thermal comfort is evident yet, does not necessarily support its influence on cooling the microclimate in many cases. The influence of shade to cool the urban spaces is discussed separately in section 3.4.1.

2.7.2. Air movement and local cooling

Thermal sensitivities are different for different parts of the body and are different depending on whether body parts are exposed to heat or cold (Zhang, 2003). For instance, it is reported that face cooling can improve thermal acceptability – the upper boundary of an acceptable range of room temperatures may shift from 26° to 30.5° C when face cooling is provided (Zhang and Zhao, 2008, 2007). People normally adapt their clothing or clothing layers to air conditioned spaces or intended activity (Zhang and Zhao, 2007). However, to assess local thermal sensation and comfort, it is important to quantify local segmental ventilation to adjust the dry and evaporative resistances of clothing for use in predictive models of comfort.

Applying a 20.3 cm² thermode, revealed that the sensitivity of body parts to cold follows this order, from lower back (most sensitive), upper back, chest, abdomen, upper arm, calf, forearm, to thigh, cheek and forehead (least). Also, the sensitivity of body parts to warmth follows this order, from calf (most sensitive), thigh, upper arm, forearm, back, shoulder, abdomen, to chest, cheek and forehead (least). The experiences of thermal sensation in different parts of the body integrate to form an overall thermal sensation and perception of comfort (Zhang, 2003).

Cheong et al. (2007) reveal that all segments of a body when it feels cold prefer a slightly warm sensation. At neutral, the lower body segments of calf, foot and head prefer a slightly warm sensation while the upper body parts of stomach, chest and back prefer a slightly cool sensation. When slightly

warm, the whole body prefers a slightly cool sensation. In addition, the hand and lower body – the thigh, calf and foot – prefer a warmer sensation than the parts of the upper body parts – stomach, chest and back – do. This knowledge can be used to improve thermal comfort if such models can be coupled with bio-heat modelling to predict thermal response in humans.

Zhang and Zhao (2008) conducted an experiment for subjects who felt warm and slightly uncomfortable in uniform conditions and found that facial thermal sensation was equal to overall thermal sensation. When means of cooling the face were supplied, the thermal sensation in the face dropped immediately from warm to slightly cool and overall thermal sensation dropped as well, from warm to slightly warm, while overall thermal comfort changed from slightly uncomfortable to slightly comfortable.

After the first moment of face cooling, subjects' thermal responses changed gradually and slightly, becoming almost constant by the end of their exposure. In order to test whether the responses reached a steady state, repeated measures were performed and it was found that the responses obtained in all conditions reached steady state in 20 min ($p>0.05$) Figure 13 & Figure 14. The subjects' responses were then divided into three groups: responses to steady and uniform conditions (the first two votes), responses to dynamic conditions (the 3rd vote to the 15th vote) and responses to steady and non-uniform conditions (the last three votes).

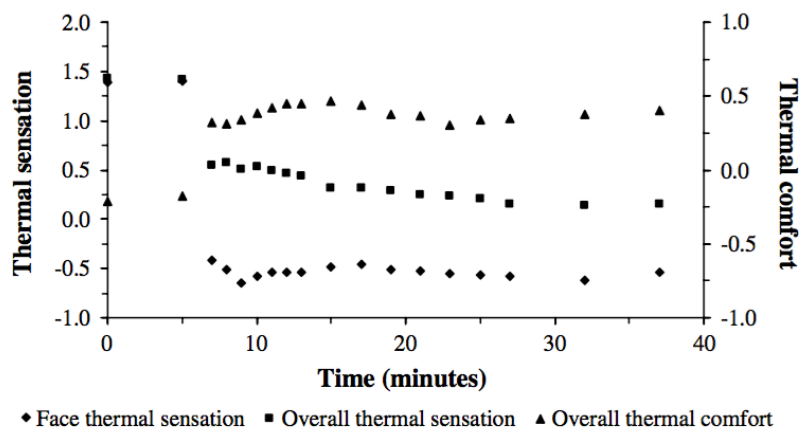


Figure 13 Thermal responses change with time in a face cooling condition (room temperature 35°C, target temperature 22°C, face cooling was supplied at 7th minute). Source: Zhang and Zhao (2008)

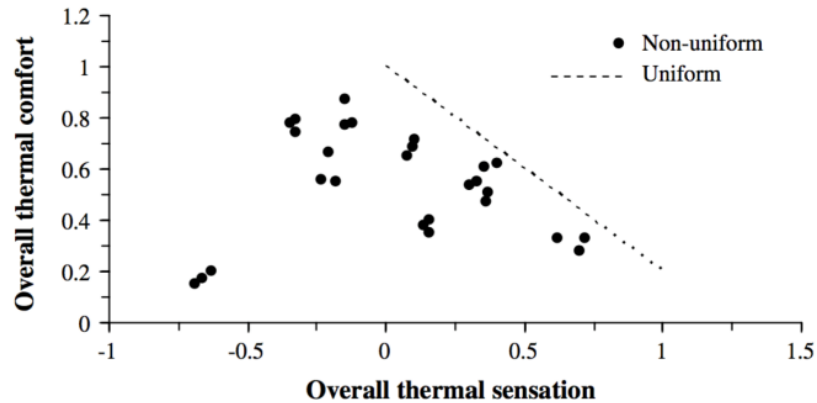


Figure 14 Overall thermal comfort as a function of overall thermal sensation under the non-uniform conditions. Source: Zhang and Zhao (2008)

These findings stimulate the potential of using wind to provide face cooling. In hot conditions, skin moisture (sweat) can promote such feeling is designed wisely. However, this depends mainly upon the presence of wind. It is important to realize that clothing is influential on thermal comfort in the presence of wind where a variation of 0.1 clo is sufficient to change comfort evaluations. The dry and evaporative resistances of clothing are reduced by wind and motion (Havenith et al., 1990).

Havenith and Nilsson (2004) and Havenith et al. (2000) suggest improvements in thermal indices to incorporate the effects of body and air movements by empirically correcting clothing insulation. Increasing external air velocity to alleviate local thermal discomfort in these segments without causing a draught is another means of improving comfort. To assess local thermal sensation and comfort, it is important to quantify local segmental ventilation to adjust clothing's dry and evaporative resistances for use in predictive models of comfort. Clothing design typically incorporates low permeable fabric, which results in thermally uncomfortable sensations for the subjects. Changing clothing designs by using higher permeability fabric for the torso results only in improving thermal sensation and only when combined with an increase in the air circulation from 1 m/s to 1.5 m/s.

2.7.3 Reduce the dependence on air-conditioning

The air-conditioned spaces referred to in this research are indoor spaces that is mechanically ventilated and set to a certain air temperature. The mechanical air conditioning system operates based on a thermostat placed inside a space measuring its temperature regularly in order to regulate the flow of air according to the desired temperature. Therefore, spaces that are mechanically controlled provides much higher levels of uniformity in its thermal conditions compared to naturally ventilated spaces. This also depends upon its geometrical composition and its anthropogenic heat

sources. Therefore, a person in an air-conditioned space can maintain his/her thermal neutrality due to the uniform and steady thermal influences.

Höppe (2002) remarks that, to predict comfort, the thermal history of a subject which can hardly ever be standardized, is important. So, in summertime, for example, it makes a great difference whether or not a subject entering an outdoor scenario has come out of an air-conditioned room. Schuh (1993) demonstrates that repeated exposure to conditions which are slightly too cool or warm for comfort, can enhance body fitness and endurance. This suggests that keeping air-conditioned spaces at a constant temperature reduces body fitness and the capacity to adaptation to an outdoor non-uniform environment.

There have been various reports over the past thirty years of heat-related illnesses due to the sudden exposure to outdoor heat of people who were accustomed to air-conditioning indoors. Nevertheless, the adaptation to neutral air-conditioning in an indoor environment often results in thermally uncomfortable responses among city dwellers, particularly in warm climates (Dahlan and Gital, 2016; Kannan, 2012; Hitchings and Shu Jun Lee, 2008; Liao and Cech, 1977).

Dahlan and Gital (2016) contend that air-conditioned building interiors in hot-humid areas have resulted in thermal discomfort and health risks for people moving into and out of buildings. The instantaneous change in air temperature can cause abrupt thermoregulatory responses. Assessments by thermal sensation vote (TSV) and thermal comfort vote (TCV) when moving through spaces with distinct thermal conditions were conducted in an existing single-storey office in a hot-humid microclimate, maintained at an air temperature of 24° C (± 0.5), a relative humidity of 51% (± 7), air velocity 0.5 m/s (± 0.5) and mean radiant temperature (MRT) of 26.6° C (± 1.2). The office that was measured led on to a veranda that showed the following semi-outdoor temperatures: air temperature 35° C (± 2.1), relative humidity 43% (± 7), air velocity 0.4 m/s (± 0.4) and mean radiant temperature 36.4° C (± 2.9).

Subjective assessments from 36 college-aged participants, consisting of thermal sensations, preferences and comfort votes were correlated against a steady state predicted mean vote (PMV) model. Local skin temperatures were included to observe physiological responses due to a thermal transition. The TSV for the veranda-office transition found no significant means difference with the TSV office-veranda transitions. However, TCV collected from warm-neutral transitions (0.24, ± 1.2) and neutral-warm ones (0.72, ± 1.3) reveal statistically significant mean differences ($p < 0.05$). Sensory and affective responses of thermal transition after moving from warm-neutral-warm conditions did not

replicate the hysteresis effects of brief, slightly cool, thermal sensations found in previous laboratory experiments.

Participants in this study were acclimatized to the hot and humid microclimate conditions and had undergone 15 min of adaptation period before the experiment. The first two thermal sensation votes, taken 5 mins apart, showed that participants felt the thermal condition on the veranda was warm at 1.9 (± 0.8) and 1.5 (± 0.9), for Vt1 and Vt5, respectively. Similar thermal sensation responses were detected 5 mins after leaving the office, where the TSV values for V2t1 and V2t5 were 1.6 (± 0.9) and 2.0 (± 0.8), respectively.

However, the TCV responses 5 mins after entering the office revealed statistically significant differences ($p < 0.05$). The TCV collected from the former and latter transitions were 0.24 (± 1.2) and 0.72 (± 1.3), respectively. These differences suggest that 20 min exposure to an air-conditioned interior of 24° C can reduce the levels of thermal comfort encountered with hot and humid outdoor conditions. Participants' thermal acceptability votes suggested that they were tolerant of the warm semi-outdoor conditions and quite content with their air-conditioned office. However, the participants were less tolerant of the warm semi-outdoor conditions for the first 5 mins after leaving the air-conditioned office.

Chen et al. (2011) maintain that in Taiwan, where air-conditioning is the most frequently used means of adjusting the indoor thermal environment to accommodate the hot and humid climate, the people who worked or lived in the air-conditioned buildings constantly encountered a step change in air temperature upon entering or leaving a building, sometimes to a substantial degree on hot summer days. The instantaneous change in temperature can bring discomfort or even risk thermal stress, such as contracting a cold, to those who regularly must move across the temperature ramp.

Makaremi et al. (2012) argue that human beings cannot naturally adapt to prefer warmer temperatures. This is in agreement with Chun et al. (2008) and de Dear et al. (1993), who found that people who experienced a warm sensation when in a warm outdoor temperature preferred a slightly cooler indoor temperature. According to (Parsons, 2014), however, people become acclimatized to the conditions to which they are exposed. Parsons refers to workers who spend long hours exposed to direct heat, such as construction workers. The study reports that, among acclimatized local Malaysian university student participants, tolerance to hot-humid outdoor conditions is higher than that of their international counterparts. This implies that the participants in this study were accustomed to air-conditioned indoor conditions and were not fully acclimatized to hot-humid temperatures when experienced with abrupt warm-neutral-warm temperature step changes.

Although ASHRAE Standard 55 was never intended to require air-conditioning for buildings, it is very difficult in practice to meet the standard's narrow definition of thermal comfort without such mechanical assistance, even in relatively mild climatic zones. But the energy costs of providing this constant supply of uniformly conditioned air are significant, as are the well-known environmental consequences associated with this vast energy consumption.

People living year-round in air-conditioned spaces are quite likely to develop high expectations of homogeneity and uniform temperatures and may become quite critical if thermal conditions deviate from the centre of the comfort zone they have come to expect. In contrast, people who live or work in naturally ventilated buildings, where they are able to open windows, become used to experiencing inherently more variable indoor thermal conditions that reflect local patterns of daily and seasonal climate change. Their thermal perceptions – both their preferences and their tolerance – are likely to extend over a wider range of temperatures than are currently reflected in the comfort zone stipulated by ASHRAE Standard 55.

2.7.4. The role of transitional spaces

The term 'transitional', is often used synonymously with the term 'transient', leading to confusion about whether we are talking about architectural space, the response and behaviour of its human occupants, physical conditions, or some combination of these concepts. Indoor spaces connected by wide openings to the outdoor environment, such as downtown shopping centres, shopping malls or pedestrian passages are found in Europe and Asia (Schaelin, 1999). In Japan, a *hantogaikukan* is defined as a semi-outdoor urban facility located between buildings (Tsujihara et al., 1999), much like the covered streets, arcades or passages in western Europe (Potvin, 2000). Similarly, thermal response and physical measurements have been taken in semi-open spaces, such as underground shopping malls and railway-station malls, common everywhere in Japan, which have open entries and do not rely on HVAC systems, (Chun and Tamura, 1998, 1996).

Measurements were taken in what researchers called the "buffer zones," the continuous spaces from the inside to the outside of buildings, such as the entry atrium space in a hotel lobby. The middle area refers to a covered balcony, porch, veranda or sunroom. These spaces are adjacent to a dwelling or serve as a passage between multiple dwellings (Nakano et al., 1999; Yamagishi et al., 1998; Yamazaki et al., 1996). A further Japanese refinement in the architectural definitions of transitional spaces is the concept of *tyukan ryouiki* (the spaces where *uchi* and *soto* meet). *Uchi* (inside) refers to interior space which is related or belongs to or possesses adjacent outdoor space and *soto* (outside) is conversely related to *uchi*.

Transitional zones are the “in between” architectural spaces where the indoor and outdoor climates are modified without mechanical control systems and where occupants may experience the dynamic effects of this change. Chun et al. (2004) divide transitional spaces into three categories (Figure 15). Type 1 is a transitional space contained in a building, such as a hotel lobby or entry atrium where conditions are constantly mixed as people move in and out of the building. Type 2 features an attached, covered space connected to the main building (or between buildings, where outdoor conditions predominate, such as a balcony, porch, corridor, covered street or arcade). Type 3, transitional space, is not attached to a building and is essentially an outdoor room, entirely influenced by the way in which the design of the structure modifies the outdoor climate, such as a pergola, bus station or pavilion.

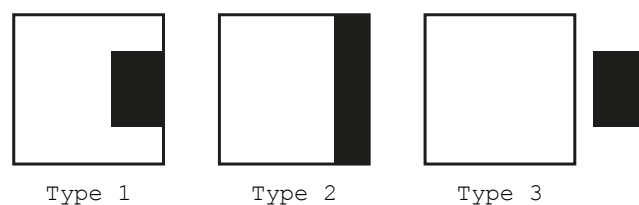


Figure 15 Shows the three transitions used in the study. Source: Chun et al. (2004)

We can see the most effective transitional space design would differ according to its purpose of that space and the climatic conditions. Type 1 would be an effective form of buffer zone in extreme climate, which would help to relieve the shock to the human body and reduce energy loss. Type 2 would be effective for cutting the effect of wind, so this kind of transitional space would help to bring down air velocity in a windy area; moreover, certain balcony designs can induce air into the adjacent room. Type 3 is effective in cutting solar radiation, so it would be welcomed in a tropical climate. The physical environment in a transitional space is varied by their type and architectural characteristics. They help to relieve the shock to the body and reduce energy loss and this kind of transitional space is effective in extreme climatic conditions (e.g. in a lobby). Another type of transitional space in a tropical climate gives a cool feeling to people outside by cutting solar radiation (e.g. a pergola). Transitional spaces help to save energy if they can be designed according to their climatic needs.

Katavoutas et al. (2015) note that in their simulation results the response of a person coming from the same neutral indoor climate varies according to the scenario followed by the individual when outdoors. The combination of radiation field (shady or not), the kind of activity (sitting or walking) and the outdoor conditions significantly differentiates the thermal state of the human body. Therefore, 75 % of the skin’s wetness values do not exceed the thermal comfort limit at rest for an individual sitting

in shade. This percentage decreases dramatically, to less than 25 % under direct solar radiation and exceeds 75 % for a walker under direct solar radiation.

Dahlan and Gital (2016) examined the subjective and physiological effects of thermal transitions in the thermal comfort zone under a roofed open-air veranda. This was to simulate the way in which people use indigenous buildings to avoid intense heat exposure in hot-humid climate countries such as Malaysia (GhaffarianHoseini et al., 2014; Zin et al., 2012; Hanafi, 1994; Lim, 1987). The study recommended that future investigations should examine the possibility of reducing the temperature difference in transient hysteresis-effect- driven conditions between air-conditioned indoor and warm outdoor conditions, to suggest more suitable indoor and semi-outdoor passive design strategies in hot-humid countries. Methods to reduce the hotter outdoor air temperature should be taken into consideration to complement neutral indoor temperatures. Gagge et al. (1967) claim that when the body has undergone a hysteresis effect from neutral to warm, the effect is less noticeable and could be overlooked unless a judgement immediately after the transition is noted. It is believed that less noticeable hysteresis effects are partially a result of reduced thermal stress.

2.8. Conclusion

The entire studies that dealt with outdoor thermal comfort confirms that pedestrians' behaviours, walking patterns, their frequentation and preferences in urban settings, depend on the microclimatic conditions offered by the built environment. In order to improve the design of the urban spaces and influence pedestrians experience, accurate predictions of the comfort limits should be made for each climate, which has its own characteristics. Methods used for prediction should be based on validated models, which consider the heat exchange between the human body and the environment as dynamic. They should account for the dynamic aspects of the course of human thermal adaptation such as that pedestrians experience. If static indices such as PET, PMV, OUT-set... etc. were used due to the lack of established dynamic methods, the metabolic rates should be considered differently. For instance, pedestrians thermal comfort could reflect different metabolic rates at different parts along their journeys allowing those static indices to account the differences of thermal levels at the start, after 3min or after 10 minutes of walking. Being aware of the thermal transitions endured along a pedestrian's journey is critical when aiming to evaluate their overall thermal comfort and thermal sensation.

The differences between thermal comfort and thermal sensation of individuals after transitions highlights the importance of the psychological parameters when investigating thermal comfort. Simple thermal environmental factors or thermal comfort indices cannot fully account for the influence of the thermal environment on the number of people using public spaces. Psychological

factors of thermal adaptation, such as experience and expectation, play a very important role in outdoor thermal comfort. Therefore, incorporating the psychological factors should be mandated in comfort prediction and investigated through outdoor field surveys of the local people. This contributes vitally to the design of more comfortable outdoor spaces in urban areas.

Improving pedestrians thermal comfort in the hot and humid conditions of Dubai, is potentially viable through shade and wind. Shaded spaces are always perceived cooler and provide a heat stress relief that is capable of improving pedestrians comfort instantly. Wind inevitably promotes cooling, yet, conditional to clothing values. Clothing designs with higher permeability fabric for the torso improves thermal sensation when wind speed increases from 1 m/s to 1.5 m/s. Besides, the notion of local cooling to certain body parts proved to have significant influences on improving people's thermal sensation. The effectiveness of the different body parts in warm or cold conditions should be well-thought-out in this case.

The large thermal distance between indoor and outdoor temperatures where the step transition is upwards, away from the comfort range proved to deter thermal comfort significantly. The role of transitional spaces, which reduces the thermal distance between two sequential spaces is greatly needed in the local climate. People who were accustomed to air-conditioning indoors proved to have less ability to adapt to natural weather conditions, particularly in warm climates. Therefore, reducing the severe dependence on air-conditioning in Dubai and pushing people to walk, would in itself encourage walkability on the long term.

CHAPTER 3: The Microclimate of Urban Spaces

Variations in the configuration of urban spaces can generate significant modifications of microclimatic parameters (e.g. temperatures, relative humidity and the wind speed). These modifications influence the wellbeing and the thermal comfort of the pedestrians in these spaces. The quality and the intensity of each activity (social or individual) within these spaces are affected by the thermal level of discomfort experienced by the individuals when they are exposed to the microclimatic conditions of a given place (Givoni et al., 2003).

Urban morphology can be defined independently of microclimate and pedestrians' thermal comfort. We consider it an independent variable. Microclimate is a variable that depends on the urban morphology, and other factors such as the state of the general and local climate. It is considered an intermediary variable. While, pedestrians' thermal comfort is a variable which depends on the urban morphology, microclimate attributes and the adaptive opportunities in urban space. Therefore, it is essential to articulate the urban morphology in ways that will improve the microclimate and thus the thermal comfort conditions. To be able to do this, one should understand how the morphological characteristics of an urban space impacts the microclimate. This is mainly influenced by the geometry and materiality of the built forms, vegetation and water, as well as strategies for limiting the generation and impact of anthropogenic interference (Thapar and Yannas, 2008).

This chapter focuses on the literature that handles how the microclimate interacts with the built environment in hot urban areas in response to the urban design attributes mentioned above. Possible mitigation techniques at an urban canopy scale which may be applied in outdoor spaces are reviewed with a view to providing a rational outdoor space design that impacts better on pedestrians.

3.1. The urban canopy layers

Climatologists have been working on different scales for quantifying the urban atmosphere, named the urban boundary layer (UBL) (see Figure 16). The UBL is the entire volume of air filling an urbanized area. This layer is defined by the climatic conditions, the built environment and the activities taking place within the city. It is divided into multiple sub layers, each with a number of climatic variables involved and possible interventions to modify the microclimate. The lowest part in the UBL is called the urban canopy layer (UCL), sometimes referred to as the pedestrians' level (Erell et al., 2011). This study focuses on the behaviour of the environmental parameters in this layer, which primarily affects pedestrians.

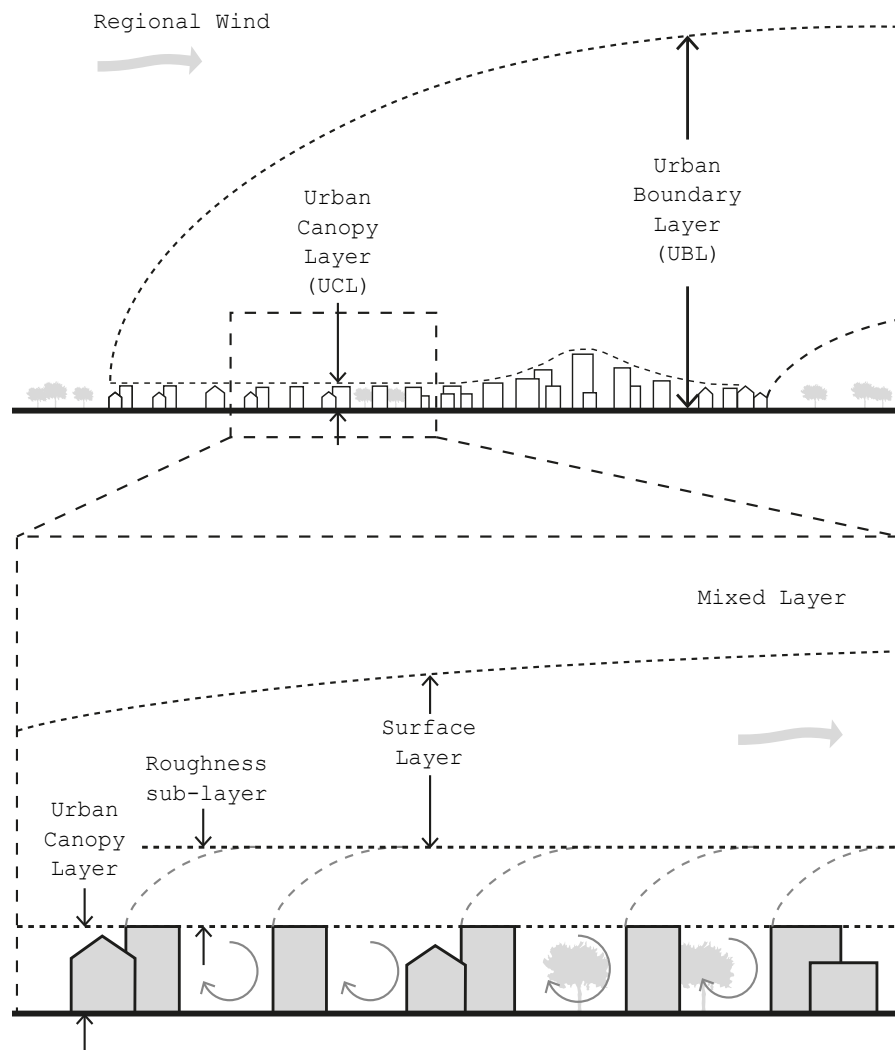


Figure 16 Schematic section of the urban atmosphere, showing the development of the urban boundary-layer (UBL) relative to the urban canopy-layer (UCL), which reaches the average building height (top), the distinction between the homogenous surface layer above the city and the heterogeneous urban canopy layer (bottom). The mixed layer and the roughness sub-layer are transition zones above and below the surface layer, respectively. Source: Erell et al. (2011).

Due to the inherent heterogeneity of the UCL, any given urban space has a unique microclimate inside it, whose air temperature, wind flow, radiation balance and other climatic indicators are determined by the physical nature of the immediate surroundings as well as the urban and regional environment. Most of the literature reviewed shows that the first control mechanism for controlling the climate is the urban layout (Bourbia and Awbi, 2004). However, the proportions of the urban spaces, the thermal and optical qualities of its finishes and the use of landscape vegetation are the design parameters that modify climate at this level. Because urban design may have localized impacts such as these on outdoor thermal comfort and building energy loads, the microclimate of urban spaces is properly considered an architectural issue. The term microclimate is in fact defined as ‘the climate that prevails at the micro-scale level’. The micro-scale refers to the smallest realm (hundreds of meters) where

individual structures and trees cast shadows and divert the flow of wind, and where built elements as fine as balconies and textured wall cladding modify the reflection of sunlight and the radiant temperatures to which people are most directly exposed (Erell et al., 2011).

3.2. Outdoor environmental parameters

There are numerous parameters within the outdoor environment. The dominant parameters found to influence thermal comfort, in hot climates above all, are the air temperature, humidity, radiation and air movement.

Air temperature here refers to the dry bulb temperature (DBT) that indicates the level of heat in the air unaffected by radiation and humidity. In hot climates, air temperature mainly depends on heat gain rather than on the solar radiation levels influencing the convective process of heat loss and gain throughout the day. Al-Sabbagh (2011) suggested that when aiming to improve the ambient air temperature in outdoor spaces, specific values of air temperature should be considered, rather than the average values. This is due to the heterogeneity of various surface temperatures affecting the mean radiant temperature, which can exert more influence depending on a person's position and activity within the space.

The mean radiant temperature (MRT) can be described as the mean temperature of all the surrounding surfaces within a space. This depends mainly on the materials of these surfaces, which specifies the amount of solar heat they absorb and release including the duration of this process. The tightness of the space greatly affects the heat gain and loss (Lin et al., 2010). It was shown repeatedly (Balakrishnan, 2012; Lin et al., 2010; Yannas, 2008) that in hot climates the MRT is a major concern which significantly increases the heat stress of individuals.

Air movement is a very important microclimatic parameter with a major influence on thermal comfort in hot and humid climates such as that of Dubai. Wind penetration is preferable within the urban layout because it promotes the dissipation of heat to the atmosphere. It also has a spreading effect which if managed properly can help cool spaces down. It accelerates the convective transfer of heat at on the different surfaces and accordingly the discharge of heat that has been absorbed, which can be unfavourable in some cases. Therefore, wind studies for urban designers, since its effect may provide either positive or negative modification to the microclimatic conditions.

Relative humidity (RH) is the amount of moisture contained in the air in relation to its temperature. Warmer air has looser molecular capacity and thus can hold more water than can lower air temperatures. Humid air, with more water content, has a higher capacity to store heat compared to

the dry air. Therefore, high humidity blocks the losses of heat at night, which raises the air temperature. It also influences the thermoregulation of the human body affecting the sensation of thermal comfort when combined with high temperatures (Nikolopoulou and Lykoudis, 2006). In Dubai, high relative humidity levels range between 40% and 85%, which is usually perceived as the most bothering aspect of the weather.

3.3. The built environment

Building settings create urban patterns that control the wind direction and solar gain and hence the thermal comfort levels of the outdoor spaces and energy consumption of the indoor ones. In Dubai, field measurements taken in July 2007 showed that the urban design in 'Old' Dubai (the *Deira* and *Bastakia* areas) contributed to lower T_a and MRT than were found in 'New' Dubai (the *Dubai Marina* area). This was due to the compact design and consequent well shaded streets (Thapar and Yannas, 2008). This finding was confirmed by Yang and Lin (2016) who argued that the size of street blocks, types of building material, and the design of sheltered areas was found to greatly affect the outdoor thermal environment, hence thermal comfort. However, the factors that influence the microclimate differ from one climate to another. In hot climates with higher humidity levels, such as Dubai, factors such as space morphology, space materiality, presence and type of vegetation and bodies of water are considered the most influential. These factors are discussed in more detail below.

3.3.1. Space morphology

The morphological characteristics of a space, or in other words, its urban geometry fundamentally influences the urban microclimate (Oke, 1988; Arnfield, 1988). The cycle of heat gain during the day as a result of high solar radiation and the nocturnal heat losses are managed through the space ratio and degree of enclosure of the surrounding buildings. The distance between buildings defining an open space, their settings and heights play a major role in the incoming and outgoing heat radiation and wind speed (Johansson, 2006). A loose urban morphology would increase the solar gain, reducing the amount of shade within a site which in turn lessens people's thermal comfort.

Most of the literature reviewed shows that the first mechanism for controlling the climate is the city layout (Bourbia and Awbi, 2004). From experimental observations and other research results, such as those of Swaid and Hoffman (1990), Rohinton (1993), Goward, (1981) and Arnfield and Grimmond (1998), it can be concluded that the air temperature differences between clusters are mostly influenced by the urban geometry and the surface thermal characteristics. Many researchers, e.g. Todhunter (1990), take the position that, at the microscale level, explicit considerations of urban geometry are more important than the albedo effect; namely the street to buildings height and width

relationships and their orientations. It is known that the urban geometry and the shading potential of urban mass are far more closely linked to comfort enhancement than are the surface characteristics of urban areas.

Shading has been found to be an overarching factor in creating a pleasant cooling effect. Providing more shade in the outdoor spaces of hot regions contributes to higher thermal comfort levels and more use of the outdoor ambience. The geometry of linear spaces has been identified by the H/W ratio which was used to indicate the tightness of urban canyons. Furthermore, tight urban canyons with a lower H/W ratio amplify the cooling effect at peak hours of the day more than do wider canyons with a bigger H/W ratio, mainly due to the increased amount of shade (Toudert and Mayer, 2005).

Bourbia and Awbi (2004) examined and evaluated the effects of building height and street width on the shading of street surfaces and ground for different orientations. As the orientation has a strong influence on the insulation of urban canyons, detailed simulations were performed for latitudes 26–32° N for the whole year. The findings revealed that the NS street orientation for H/W of 1.5:1 and higher can result in street shading of between 40% and 80% of the street area, whilst diagonal street orientations NW–SE and NE–SW, can manage street shading only between 30–50% of the street area throughout the year. At the latitude of 33° N, an EW street orientation can achieve shading of about 30% for an 8-months period every year, provided that a 2:1 or higher H/W ratios is used. The ratio 0.5:1 is least effective even with NS street orientation (providing less than 35% street shading). This means that under low latitude conditions streets deviating from an EW orientation may often be a desirable feature of urban design.

The study suggests that for wider urban canyons (H/W of 0.5:1), tall trees should be introduced to improve the urban canyon environment. For narrower canyons (H/W of 0.5:1), taller trees cannot be expected to improve the thermal environment of the canyon. The more open the residential sites were the warmest in the day and the coolest at night. In very hot conditions, the soft ground cover of the more open residential sites did not significantly improve daytime cooling. This suggests that shading was more central to daytime cooling than ground cover. According to Rohinton (1993), extensive tree canopy produced some cooling during the day, but at the high-density sites the cooling provided by building shade did equally well. Increasing the albedo of building surfaces by whitewashing reduces solar heat gain and the resulting storage of heat. Additionally, increasing the albedo of large areas of the city by using light-coloured dyes or sand in paving materials will lower the air temperature by reducing the absorption of short-wave radiation.

Studies confirmed that shading was an effective means of mitigating heat stress in outdoor spaces. Four different street ratios were simulated to validate the effect of the H/W ratio with reference to the sky view factor (SVF) (see

Figure 17) which is the openness of the cluster to the sky. An inverse relation exists between the H/W ratio and the air temperature, whereas the lower H/W ratio (0.5 and SVF of 0.87) contributes to higher air temperature levels than having an H/W of 4 and a SVF of 0.37, with a maximum difference of 3 K. However, a H/W ratio of 2 achieved the most appropriate balance in relation to a SVF of 0.54. it is noteworthy that the more shade in the spaces, the dimmer they become, and hence the higher the energy demand is for lighting the surrounding structures.

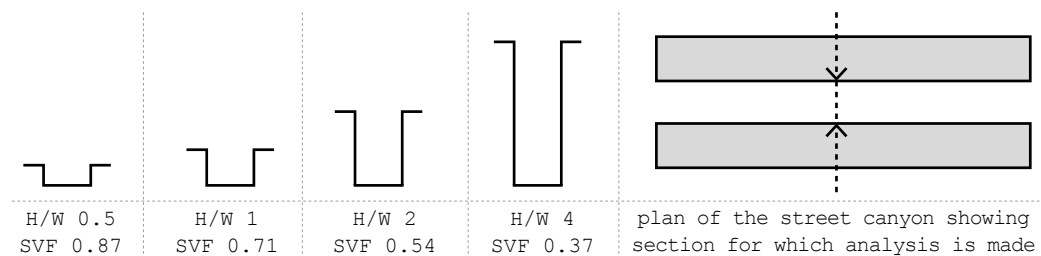


Figure 17 Schemes of simulated street canyons. Source: Toudert and Mayer (2005)

Link the effect of the space geometry to that of the surrounding buildings, which had been shown to play an important role in the microclimate. They investigate the cooling effect of colonnades in the building base, using the cluster thermal time constant CTTC model. In the Mediterranean Coastal region, for example, the maximum cooling effect of colonnades at noon in summer was found to be 3–5 K, for H/W of 0:5 and 2–3 K in narrower streets (H/W of 3). Krüger et al. (2011) observed that denser spaces contribute to higher levels of air pollution and lower levels of air temperature while less dense layouts minimize the pollution that is trapped, thus leading to higher temperatures. The study accentuated the need for a balance between the two factors.

Oke's (1988) study suggests that a ratio between $0.4 < H/W < 6.0$ is considered a good compromise between the thermal needs (high ratios) and the pollution needs (low ratios). This ratio was acceptable to Arnfield (1988) only if applied in cities with heavy cloud cover. A study in the hot humid environment of Dhaka found that on average the daily maximum temperatures declined by 4.5K when the H/W ratio increased from 0.3 to 2.8, a decline which was fair for achieving thermal comfort levels (Etzion, 1994).

Andreou, (2014) compared two sites with different characteristics in terms of street geometry and urban density, analysing the effect of parameters such as urban layout, street geometry and orientation on solar access and shading conditions. The first experiment site was a traditional settlement on the Greek island of Tinos, and the second was a relatively newly built part of the island's main town. The shading analysis shows that compact urban morphology and high H/W ratios have a positive effect on shading percentages in summer. High shading percentages are critical to pedestrian thermal comfort as well as surface temperatures.

Andreou's measurements show that air temperatures in the traditional settlement are lower than those in the contemporary site. In covered streets, the air, wall and ground surface maximum temperature difference reach 7K, 8K and 17K respectively, according to experimental measurements. Surface temperatures are mostly influenced by exposure to the sun and thus, orientation, street geometry and certain morphological characteristics play a crucial role. Their experimental measurements also show that in the traditional settlement, temperature differences at pedestrian level between opposite facades in a deep canyon are minor. This can be explained by the high H/W ratio which leads to high percentages of shade and small differences between the surface temperatures of surfaces with different orientations.

The results of the shading simulations are in agreement with the parametric thermal analysis results, according to which, when the prevailing winds are northerly, air temperature and ground surface temperature in urban canyons on the N-S axis are more favourable than canyons on an E-W axis. Surface temperatures on the walls, however, are less favourable in N-S canyons. Consequently, conditions in N-S urban canyons offer greater thermal comfort to pedestrians and lower horizontal ground temperatures, which influence the urban heat phenomenon on the island. Conditions in E-W urban canyons are more favourable in terms of facade temperatures.

The advantage of E-W aligned streets decreases as the H/W ratio increases. For a H/W ratio of 3.0 the advantage of southern facades diminishes since eastern and western elevations receive lower solar increases in the summer period. This correlates with parametric thermal analysis results, according to which for high H/W ratios no significant differences occur between façade surface temperatures on E-W and N-S aligned streets. Finally, the analysis led to the determination of a maximum H/W ratio of 0.8 in order to achieve solar access for two-thirds of the area of a southern façade and of the facades of diagonal streets on 12.00 noon in December (Figure 18). In sloping terrain, however, the H/W ratio can be higher, since the escalating morphology of buildings can supply more insulation in wintertime,

provided that southern orientation is ensured. Moreover, higher H/W ratios can be applied on streets with a N-S axis.

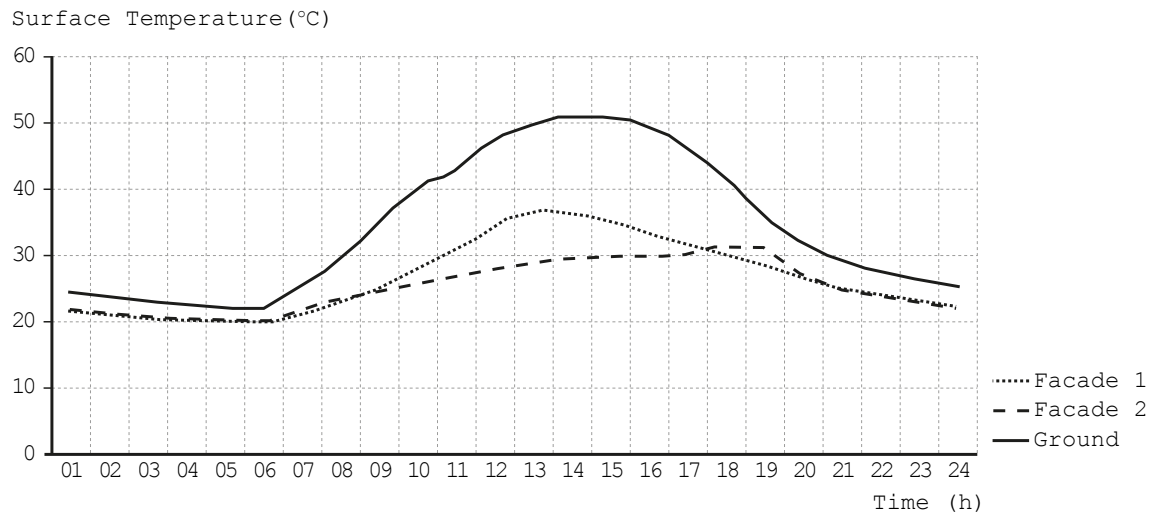


Figure 18 Ground and facade surface temperatures for an E-W canyon with tree and a h/w ratio of 0.6.
Source: Andreou (2014).

The sky view factor (SVF) method represents the shading of only a single specific point, not the shading of an entire area. Numerous studies have used this measure; but the SVF can represent the status of specific areas within a single large area. This is because a slight change in the shooting location causes significant variations in the SVF. A location with a high density of plants was considered a “shaded” location, whereas a location without shading from nearby buildings or trees was considered an “unshaded” location. Because the path of the sun in the sky differed from day to day, resulting in varying levels of shading over time, the “shaded” and “unshaded” locations were not fixed; they varied according to the sun’s movement. Nevertheless, the sunlight in the “shaded” locations was inevitably blocked by nearby buildings or trees, whereas the “unshaded” locations were necessarily exposed to direct sunlight at all times, by definition. Therefore, this index can be considered more indicative of the obstruction of the sky, which indicates the amount of shade but not of constant shade and should not be used solely for outdoor space design.

Hwang et al. (2011) also suggest that thermal comfort is best in spring, summer, and autumn in Taiwan when a location is shaded. In winter, low-shade conditions may contribute to the increase in solar radiation; thus, thermal comfort is improved when a location has little shade in winter. These writers argue that the thermal comfort conditions vary in different seasons, and that any single shading level or H/W ratio for urban streets cannot be suggested. For example, some shading devices on urban streets may be added in summer and removed in winter. Additionally, deciduous trees may prove helpful in providing shade in summer and letting solar radiation enter streets in winter.

Under low latitude conditions, the reduction of solar irradiance in the urban environment may often be an important feature in urban design. This can be achieved when the obstruction angle is large (with a high H/W ratio). Solar access to streets can always be lessened by increasing the H/W to larger values. The street canyon orientation (not the H/W ratio alone) also has considerable effect on solar shading and the urban microclimate. The paper demonstrates through a series of shading simulations and temperature measurements that many useful relationships can be developed between the geometry and the microclimate of urban street canyons. These relationships may help to formulate urban design guide-lines governing street dimensions and orientations for use by urban designers (Bourbia and Awbi, 2004).

3.3.2. Vegetation

Greenery is a valued commodity in Dubai. Green spaces have high marketing value for developers. However, large areas of greenery are expensive to maintain due to the harsh climate and cost of desalinated water. While older parts of Dubai are mostly devoid of greenery, new developments are provided with large green spaces. There is growing evidence that shading buildings by trees can help reduce the amount of energy needed for air conditioning, and that trees and vegetation in urban sites and improve the air quality and lower the ambient temperature as well as providing shade for pedestrians (Thapar and Yannas, 2008).

Vegetation incorporates several characteristics that help to reduce the air temperature and improve the microclimate. Vegetation has been shown to enhance the microclimate mainly by shading, reducing the surface temperatures and cooling through evaporation. While high shading levels in summer increase daytime thermal comfort, they can reduce long-wave radiation loss on the surface, contributing to high temperatures at night. A balance between minimizing the sun's radiation on hot summer days and allowing it in winter to maximize the heat gain has to be achieved when designing shelters for outdoor use (Hwang et al., 2011).

Shashua-Bar and Hoffman (2003) show that 80% of the cooling effect provided on 11 sites in a Tel-Aviv urban complex was due to the shading effect obtained by trees. In the day, the shade from trees reduces the penetration of solar radiation and the attenuates the thermal gains from thermal mass. A CTTC model was used for testing such effects, which exerted a considerable passive cooling effect on its surroundings. Oke (1988) explains the contribution to the cooling effect of the air exchange by long and short-wave radiations between the trees and their surroundings. The dissipation of the heat load was due to evapo-transpiration and convective heat exchange with the air. The authors argue that the cooling effect due to vegetation extends its impact on its surroundings.

The soil characteristics of a site are among the main factors affecting the microclimate. The cooling effect obtained by a green site is due to the poor ability of its soil to absorb heat, whilst the surface of the vegetation, for many reasons, has been shown to absorb much less heat. The colour and surface characteristics of plants reduces their ability to store heat internally; instead it is evaporated in an evapo-transpirational process (Robitu et al., 2006), which makes them thermal neutralizers.

The cooling influence of vegetation depends upon the types and distribution of the greenery used, the microclimate and the topographical characteristics of the site. Shashua-Bar et al. (2009) demonstrate the need to study the effect of vegetation on the microclimate in relation to the site conditions, components, site characteristics and the materials used. Vegetation as a passive cooling element has a set of interactive relations with its surroundings, depending on numerous variables. The cooling effect of a group of trees depends on the materials in the space (grass, albedo or stone tiles), the geometry of the space, its orientation and the composition of the adjacent buildings. The reactions between these variables are considered to have a complex role in the heat gained and released.

In a similar climatic region to Bar's previous study of Tel-Aviv, Shashua-Bar et al. (2009) focused on the water consumption factor of several combinations of shade and vegetation in relation to the cooling effect that they produced in an urban context. The study tested six different strategies of trees, grass and shade to find guidelines in bioclimatic design. A balance between grass and trees was chosen as the most effective in terms of enhancing the microclimate through shading and respiration. Providing shade through a canopy mesh (used in many hot arid climates) was found to be inadequate compared to that provided by trees and indeed caused a slight heating effect, up to 0.9 K. Grass tends to reduce air temperature but if not shaded (preferably by trees) consumes more water due to the fast evaporation of water. Providing grass under shade trees or a shading canopy enhances the cooling effect better than shaded areas with no grass. Yet, trees are considered the most effective in reducing cooling loads due to its high cooling effectiveness due to the shade they provide (Al Sabbagh, 2017).

However, Masmoudi and Mazouz (2004) have observed that the presence of vegetation is more effective than its quantity. The increase in the quantity of vegetation masses had no great significance compared to the influence of trees in locations under high thermal stress. The authors reveal that the best orientation of the tree line is north-east/south-west because it reduces most of the solar energy absorbed by the ground surfaces. It is important to note that densely vegetated areas find it difficult to dissipate heat at night due to the great concentration of vegetable masses (Wong et al., 2007).

Moreover, the spacing between trees is effective in cooling the thermal environment if they are distributed widely enough apart (Shashua-Bar and Hoffman, 2000). Georgi and Dimitriou (2010) examined an area of 100 m² and recommend that it can accommodate 8 trees 5m apart to achieve a

desirable thermal comfort balance throughout the year, depending on the type of tree. Simulations with BOT-world, however, show that a suitable distribution of shady places throughout an area can effectively lower thermal heat stress for pedestrians, even if their route includes passages with high radiative temperatures and PET values (Bruse, 2007).

Greenery, moreover, impedes wind speed, which is of prime importance for outdoor thermal comfort in hot climates (Mahmoud, 2011). This is due to friction with the plant canopies. Al-Sallal and Al-Rais (2012) contend that the presence of vegetation reduces wind velocity resulting in stale air at the pedestrian level. Therefore, in hot climates, landscape design should seek to optimize shade without impairing airflow (Setaih et al., 2013).

Evaluating the cooling effects of vegetation in an urban context is further complicated because they are interrelated with other building effects (Shashua-Bar et al., 2006; Stabler et al., 2005). The microclimate in an urban space is influenced by the adjacent buildings and landscape elements, and by the complex interactions between them (Erell and Williamson, 2006). Thus, conditions at different points in the urban canopy layer may differ significantly even in the same overall climatic context, and they can be affected by a variety of factors relating to geometry and surface properties (Pearlmutter et al., 2006) and also by anthropogenic heat release. It is therefore helpful to investigate the impact of vegetation in the context of planning strategies appropriate to the climatic region and to the related urban environment (Shashua-Bar et al., 2009).

3.3.3. Space materiality

The use of high albedo materials, which are characterized by the ability of their surfaces to reflect incoming solar radiation in an urban environment, is an effective technique and seen as a promising method to reduce the effects of the thermal environment on pedestrian comfort (Fintikakis et al., 2011; Akbari et al., 1992). Research evidence indicates that increasing the solar reflectance of materials by 0.25 leads to a significant reduction of the material temperature by 10°C, because it keeps the structure surfaces cooler in sunshine, thus reducing the convection of heat from the material to the ambient air (Synnefa et al., 2011; Akbari et al., 2001). Research (Setaih et al., 2013; Synnefa et al., 2011, 2008; Levinson et al., 2007) on white and light coloured surfaces has demonstrated significant improvements on thermal comfort as a result of their high ability to reduce the ambient air temperature.

Chatzidimitriou and Yannas (2015) studied the influence of form and materials on the microclimate of open urban spaces. Environmental data measured in six open urban spaces in summer were used to assess the influence of materials, vegetation, water, canopies and buildings on microclimatic

conditions and on the thermal comfort of pedestrians. The measurements highlighted an inverse relation between the surface temperatures of hard pavements and their albedo values, i.e. high albedo surfaces promote low temperatures. The converse is also true. However, detailed examination of the influence of albedo on both surface and globe temperatures reveals that although high albedo surfaces were cooler than darker surfaces, the global temperatures measured above them were higher, due to reflected solar radiation from the ground, leading to higher mean radiant temperatures and worse comfort conditions for pedestrians. These results indicate that from the viewpoint of pedestrian comfort, achieving lower surface temperatures by the use of reflective materials does not compensate pedestrians for the higher amounts of reflected radiation released in the urban environment.

Consequently, pavements with high albedo such as light coloured or “cool” materials, despite their cooler surfaces, may actually increase thermal indices and compromise outdoor thermal comfort. However, dark pavements made of materials with high thermal capacity present a significantly lower surface temperature and slightly lower global temperature than similarly dark materials with lower thermal capacity, indicating the influence of other physical properties in cases of similar albedo. Some measurements have also shown indications of the influence of material porosity and its ability to store heat leading to lowering the surface temperatures (Chatzidimitriou and Yannas 2015).

Grass surfaces were cooler than the concrete tiles and the corresponding global temperatures were lower. Tree shade had an even greater influence, with shaded surfaces as much as 20 K cooler than exposed ones and with up to 13 K lower global temperatures above them. On a day when the grass had been watered, its mean surface temperature was lower by some 3.5 K than that of the previous day when the soil was dry. Differences between shaded concrete tiles were negligible (mean surface temperatures were around 29°C); they were much cooler than those exposed to the sun. As the pavement below trees became exposed to the sun in the afternoon, its temperature rose. The lower temperatures of surfaces with grass are attributed to the high thermal mass of the soil, the soil's humidity evaporation and the shade provided by the vegetation. It has been observed that vegetated surfaces can achieve temperatures some 20 K lower than inanimate surfaces of the same colour; in urban parks vegetation creates environments that are up to 2.5 K cooler than their urban surroundings (Chatzidimitriou and Yannas 2015).

3.3.4. Bodies of water

In Dubai, the dominant presence of bodies of water in all new urban areas is meant to increase the land value. The use of artificial lakes, water fountains and water features in outdoor spaces as a bioclimatic technique to improve the microclimate is very effective in hot dry conditions (Setaih et al.,

2013). Bodies of water act as good heat sinks, particularly, in the peak thermal stress periods of the day.

In Japan, Nishimura et al. (1998) confirm that adding artificial waterfalls, spray fountains and urban canal facilities eases the uncomfortable thermal environment because it greatly reduces the air temperature (by as much as 11⁰ C). However, they increase the humidity levels due to the influence of the evaporative cooling, which is not a preferable strategy to improve pedestrians' comfort. Evaporative cooling has been a well-known passive cooling strategy yet should be used in hot dry climates. In old Dubai water bodies should be avoided, due to the high humidity and to the scarcity of water (Thapar and Yannas, 2008). Thapar and Yannas (2008) compared the air temperature and humidity levels in two new urban developments with different proximity to water. Field measurements were taken in the summer period in 'Marina' and 'The Greens'. The 'Marina' area, representative of the new urban high-rise districts, is influenced by the proximity of water and the winds blowing from the Gulf, while 'The Greens' displays the effect of vegetation and shading trees. Measured relative humidity levels were considerably higher near the sea (Figure 19). Therefore, the use of water features and lakes should be restricted in the local climate due to its poor cooling potentials, its increase to the humidity levels and also due to the water scarcity problem in this region, which should not be ignored.

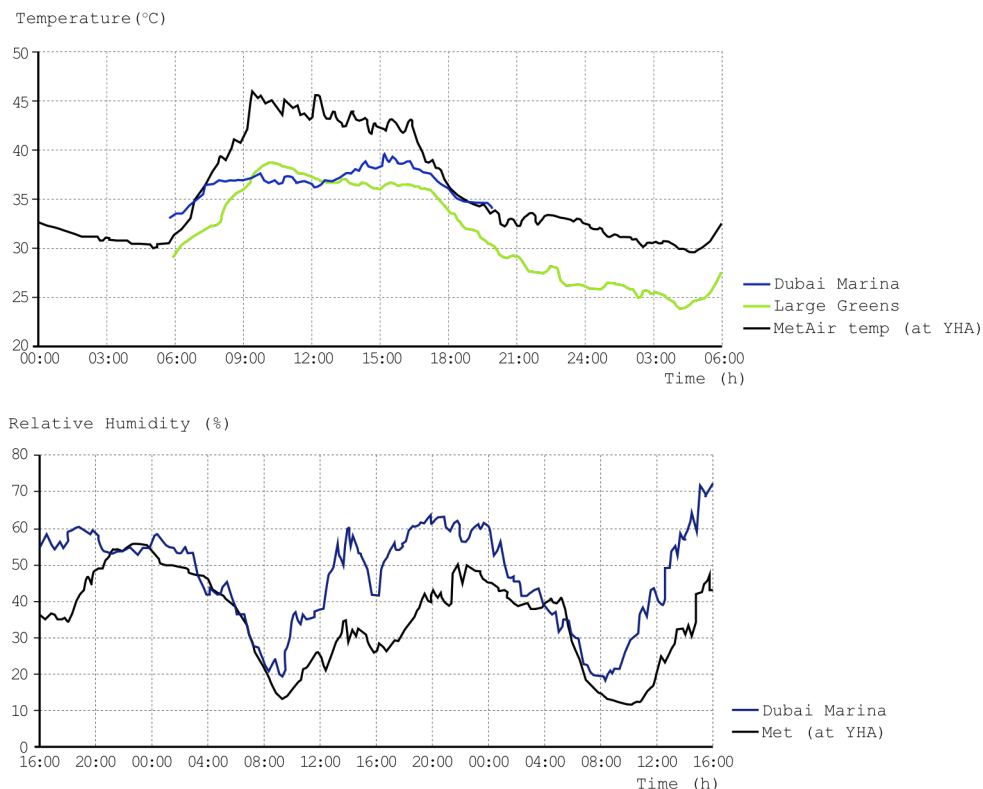


Figure 19 Measurements in Dubai Marina and Greens comparing the air temperature (top) and the relative humidity (bottom). Source: Thapar and Yannas (2008).

3.4. Improving the microclimate

Once the influences of the many attributes of the physical urban environment are understood separately, it becomes clear that the parameters are interdependent and depend on the climatic region in which they are applied. Thapar and Yannas (2008) conducted a short-term outdoor investigation to improve thermal comfort for pedestrians in Dubai, suggesting that the built form should essentially incorporate well shaded and ventilated urban spaces; transitional spaces mitigate the conditions indoors and outdoors. They also suggest the benefit of using grass to cool the ground surface temperature and reduce the MRT, in consideration of challenges such as the high humidity and the maintenance of lush gardens with their high-water consumption. Evaporative cooling may relieve pedestrians at certain times of day even during the summer months. Adaptive Activity Zoning should be exploited to create appropriate microclimates for different activities. Shading, permeability to air flow for convective cooling, and the appropriate choice of urban materials were determined as important design strategies. The study suggests the use of a microclimate model such as ENVI-met to get a rough idea of the likely effects of built form, vegetation and bodies of water on ambient temperature and airflow.

In pleasant weather, the effect of humidity is often barely noticeable. However, in warmer conditions high humidity becomes less tolerable, due to the difference in the heat exchange between the human skin and the surrounding air. Moving air causes evaporation and transpiration, which have a cooling effect. This process is reduced by the presence of humidity. Winds do not change the air temperature but rather provide a cooling effect that compensates for the effect of humidity. "Therefore, at high temperatures there is an optimum value of air velocity, at which the air motion produces the highest cooling. Reduction of the velocity below this level causes discomfort and heating ... and increasing beyond this level causes heating by convection" (Givoni, 1976).

A study in Dubai where 40% RH and 40°C were found to be tolerable so long as a good breeze was blowing reveals that an increase in wind speed can balance the acceptability of humidity (Thapar and Yannas, 2008). Another study even weighted the importance of wind speed higher than air temperature in improving thermal sensation, since it promotes the evaporation of sweat equivalent to a drop in air temperature of 5-6°C (Balakrishnan, 2012). The relation between air speed and air temperature reduction is inversely proportional; for a 1°C increase in air temperature, 0.5 m/s are needed to remain comfortable (Krüger et al., 2011).

Al-Sallal and Al-Rais (2012) conducted an airflow analysis in a modern urban context in Dubai, aiming to understand the relationship between urban geometry and thermal comfort. The study yielded considerable findings. The wind flow lessened when the wind hit the buildings, funnelled by the wider

street canyons, then increased once again as it moved towards to a free stream. Wider canyons with an aspect ratio of 1.75 encouraged a more comfortable wind velocity. But in open spaces the velocity increased significantly. In longer street canyons bounded by building blocks on opposite sides, the wind velocity remained stable at low values of 0.5 m/s. Wind speed was reduced when the wind hit the buildings, creating vortices at the corners of buildings, which made pedestrians uncomfortable. However, the study did not include social surveys that might have validated such findings.

The design of a street is a key issue in the bioclimatic design methodology of urban spaces. It is the interface of architectural and urban concerns, because it consists of the surfaces shared between the buildings and the open urban canopy. A good space design should provide comfort for pedestrians and to promote the cooling of building structures and the reduction of external heat gains. Street design requires deeper consideration to the wind direction along with other climatic factors such as amount and hours of solar radiation and the humidity levels (Al-Sallal and Al-Rais, 2012). Therefore, design interventions should be selected based on specific site parameters.

Balakrishnan (2012) concludes the same and mentions that the prime factor in pedestrian comfort in the United Arab Emirates (UAE) is shade. She measured the air temperature under different shading methods and found that building shade reduces the temperature by 1.3°C. A fabric awning recorded a 0.2° C reduction, a banyan tree recorded a 3.2° C loss and a palm tree reduced the temperature by 0.5°C. However, a PVC shading structure worsened the thermal sensation due to the rise it produced in air temperature, of 11°C higher than that outside it. This was due to the rise in the radiant temperature (Balakrishnan, 2012). Such findings reveal the need to choose appropriate materials for the shading element for the desired level of cooling.

Paolini et al. (2014) maintain that increasing the solar transmittance of shading surfaces, demands the evaluation of alternative comfort control strategies such as increasing air circulation and reducing the surface temperature of the surroundings. However, in standard conditions too little air circulates underneath the tent and in the urban canopy; hence, shading devices that do not prevent air recirculation (i.e. the convective mixing of the air from the canopy with the air above the canopy) should be addressed in future developments. The possibility of closing the tent over the canopy at night should also be considered to aid the flushing effect. The study found that adding a canopy for shade did not significantly alter the air circulation, due to the weak wind speed of 1m/s in the experiment, while reducing the solar access is crucial for mitigating the microclimate at the canopy scale, especially in view of the pavement surface temperatures. Therefore, in areas of low wind velocity shade should be prioritized regardless of the wind.

A study (Lin and Matzarakis, 2008), performing shading analysis for specific days provided some recommendations derived from the results that it obtained regarding the renovation of open spaces in cities with a hot climate. First, the design phase should take into account the daily shading patterns for the main focal point of the open space. Second, the use of shading devices should be in accordance with the main uses of the space, providing shade when it is most needed. For example, a square which is mostly attended in lunch breaks should have numerous sitting areas that are shaded at lunch time, or a square used as a playground for children after school should be shaded in the afternoon, etc. Third, horizontal shading devices should be provided to improve thermal comfort in the midday hours, when no significant shade is cast by surrounding buildings. This recommendation extends also to urban environments with a high floor area ratio, such as historical city centres. If the specific urban qualities of the place or design features limit the use of greenery, movable artificial shading devices can be brought in, ensuring solar access in winter. On the whole, multiple types and levels of shading are suggested, in order to fulfil people’s different preferences for thermal conditions.

3.5. Other urban design factors

There are many design objectives that urban designers and planners have been charged with when creating pedestrian-friendly communities. These objectives include thermal comfort, safety, human scale, linkage, visual enclosure, complexity, coherence and a sense of place (Ewing, 1999), not to mention beauty. Kumar (2010) classified the factors that influences walkability into three categories: the natural environment, the built environment or other personal factors, as shown in Table 3. The factors within each category are dependent and interconnected to one another and cannot be enhanced independently as a way to promote walkability. For example, natural factors such as topography of the area and the climatic conditions does not determine the attractiveness of the area to pedestrians.

Table 3 Factors affecting walkability. Source: Kumar (2010).

Natural Environment	Built Environment	Personal Motivation
Topography	Land use pattern	Physical condition (age, health)
Climate	Distance	Family background
Time of day	Connectivity	Education
Day of week	Design of the pathway	Attitudes and values
	Quality of the pathway	Profession
	Safety	Cost (time and money)

Other factors within the built environment such as the land uses, the distances between the facilities, the safety of the neighbourhood and the quality of the pathway also determine the attractiveness of the environment to pedestrians. For instance, urban areas that lack ‘safety’ would abandon walkability

even when the weather is pleasant, and pathways are designed beautifully. Personal factors such as the pedestrian's health, background, education...etc., also influences people's willingness to walk and are sometimes challenging to identify in areas that lack walkability. This is due to the ambiguous nature of such parameters that differs from one place to another. Therefore, the prominence of any of the factors presented by Kumar depends on the social, cultural and political nature of the area that they are being applied to.

Urban designers and planners should be able to identify the factors that defer people from walking at urban areas before seeking design resolutions that focus on one or more factor to improve the public realm. There is a necessity for a holistic urban design approach that considers all factors in a synthesized method to promote communities of walkers. Therefore, in this study, pedestrian's friendly areas that have a dominant presence of pedestrians along the utilitarian routes during the mild climatic conditions have been identified for investigation. The lack of pedestrians during the hot and warm period along these routes assures the influence of the climatic factor, while other factors meet the standards for designing walkable communities.

3.6. Conclusion

The microclimate of the outdoor environment can be controlled by the details of the design of the built environment. The urban density and geometry influences the solar penetrations on the different materials that can store heat, and the trapping of radiation by multiple reflections between buildings and street surface. Avoiding overheating by solar radiation in summer should be reduced with compact designs and means of solar protection such as trees and shading elements. However, this should not impair airflow, which leads to the trapping of heat during evenings. The lack of air movement is influential on the thermal environment and has a significant warming effect in hot humid conditions. Careful selection of the shading technique that considers the heat exchange taking place in the urban canopy layer and ensuring ventilation, are more effective ways of cooling the microclimate.

The materiality of outdoor spaces also has a significant impact on the mean radiant temperature, one of the crucial parameters in hot climates. Primarily the blockage of direct solar radiations should be chosen. However, if materials are not selected carefully urban design configurations that reduce solar penetration will still suffer from the impact of indirect radiations.

Vegetation incorporates several characteristics that help to reduce the air temperature and improve the microclimate. Trees provide shade, reducing the surface temperatures and cooling through evaporation. Although high shading levels increase thermal comfort during the day in summer, they

can reduce long-wave radiation loss on the surface, contributing to high temperatures at night. A balance between diurnal gains and nocturnal losses should be managed when landscaping outdoor spaces and pathways. Yet, a drawback of greenery is that it impedes wind speed, which is of prime importance for outdoor thermal comfort in hot and humid climates. This is caused by wind turbulence caused by plant canopies.

Shaping the built environment to create more conducive outdoor spaces requires a profound understanding to the microclimatic conditions of the different spatial characteristics in real urban setting. The design of a street is a key issue in the bioclimatic design methodology of urban spaces. It is the interface of architectural and urban concerns because it consists of the surfaces shared between the buildings and the open urban canopy. Efficient designs should provide thermal comfort for pedestrians for longer times of the year by promoting outdoor cooling.

PART II: FIELDWORK AND ANALYTICAL STUDIES

CHAPTER 4: Social Surveys 01: Setting the Comfort Limits

In Dubai, and the gulf region, it is extremely challenging for urban designers and planners to predict thermal comfort due to the lack of validated outdoor comfort indices or investigations. Therefore, extensive fieldwork has been conducted to set the limits of pedestrians' comfort. This chapter reports on the findings of the investigations done to assess the thermal comfort and thermal sensations levels in a range of microclimatic conditions and seasons along utilitarian daily walks to such destinations as their work, school, the metro, the mosque, etc.

4.1. The context

Two urban districts were selected for the field investigation, named *Greens* and *Jumeirah Lakes Towers (JLT)*. Both exemplify new urban communities in Dubai as *Jumeirah Beach Residences*, *Discovery Gardens*, *Mirdiff*, etc. Their size, urban typology, landscape, water features and facilities, encourage their denizens to walk. The outdoor environment provides a variety of shaded conditions. Utilitarian trips between facilities in pleasant weather conditions could be dominantly identified, making them suitable for the present investigation.

4.1.1. Jumeirah Lakes Towers

Jumeirah Lakes Towers (JLT) is a mixed-use (residential and commercial) development, which consists of high-rise towers, 35-45 storeys high, constructed around artificial lakes and a park (Figure 20). The area is covered by landscaped walkways, shown in

Figure 21, and accommodates multiple facilities such as playgrounds, mosques, retail outlets, office buildings and hospitals. Two metro stations have been built in 2009, which have rejuvenated walkability within the neighbourhood. Pedestrians attendance is also dominant nearby many other metro stations across the city.

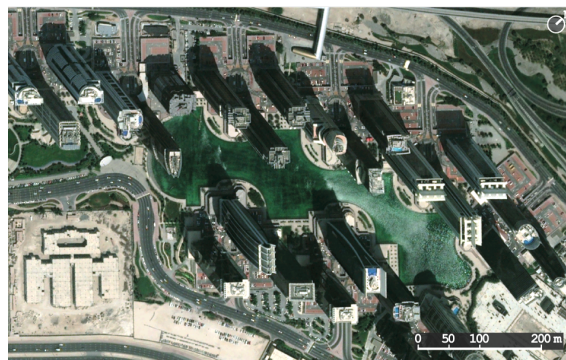


Figure 20 Map of Jumeirah Lakes Towers showing the urban fabric. Source: Google Earth extracted (2015).



Figure 21 Images of pedestrians walking in JLT to the metro station, offices and other facilities at different times of day and year.

4.1.2. The Greens

The Greens, like other areas in Dubai, is a non-gated development with defined boundaries. The community consists mainly of low rise, 5-7 storey blocks, with a strip of high rise, 30-35 storeys only on its western edge, shown in Figure 22. The district has a quiet ambience with multiple facilities, such as retail centres, a school and nurseries, a community centre and many leisure gardens, Figure 23. The area along both sides of the lake accommodates pleasant pedestrian walkways, which are heavily occupied in the mornings and evenings. The urban fabric of the community has taken care to encourage walkability, as evidenced in the design of the side walkways and scale of the streets.

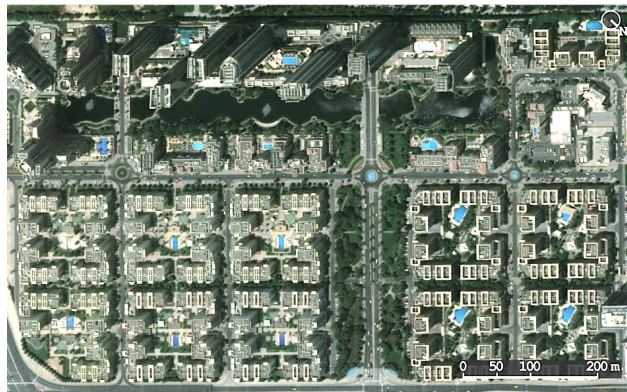


Figure 22 A map of The Greens showing the urban fabric. Source: Google Earth extracted (2015).



Figure 23 Images of pedestrians in Greens at different time of the day and year walking along the sidewalks and pathways linking the facilities.

4.2. Aim

The main goal of using this method was to identify the thermal sensation and thermal comfort levels associated with heat among pedestrians in Dubai. These were plotted on a thermal sensation vote (TSV) ASHRAE 7-point scale and a thermal comfort vote (TCV) ASHRAE 6-point scale, respectively, to quantify the data gathered and provide a base for standardization within the region for predicting thermal comfort in various microclimatic conditions. It was intended to understand other factors, such as how often people walked, how far they travelled, their perception of shade and the adaptive measures taken to cope with the microclimate. This was fundamental as the city has a metropolitan character, which makes it very difficult to specify and predict such behaviours and thus it was worth investigating.

4.3. Interviews and data gathering

The interviews involved questioning random pedestrians using a pre-set of questions (Appendix A) in the two communities where they walk regularly to get to specific destinations. In total, 300 interviews were conducted along the four utilitarian routes indicated in Figure 24, along the daily journeys to work, school, the mosque and the metro. Pedestrians along those trips were randomly approached by the investigator between 8:00-9:00, 12:30-13:30 and 16:00-17:00.

Field observations and interviews were conducted between September 2015 and May 2016 inclusive, avoiding June, July and August due to the very low presence of pedestrians during these months and the few people who did walk did not want to stop for interviews. Routes that contained different direction of pedestrians' flow were considered as a different journey due to the change in time when people walk and change in the sequence of spaces experienced. Each journey was fragmented into a set of sequential spaces based on their physical configuration and shading conditions. This created a variety of microclimatic conditions during the interviews. This also allowed to identify the influence of

the thermal conditions of the antecedent space on thermal comfort, i.e. moving from an indoor space or moving from a shaded or sunny space.

The analysis of the spaces within each journey had helped understand the different sequence that pedestrians endure before being interviewed. Journeys A and B involved pedestrians walking to school during the morning. Journey C and D involved pedestrians walking to the mosque during midday, yet, at different communities. Journeys E and F involved pedestrians walking to and from the metro station and offices. Diagrams for the journeys that were analysed are shown in Appendix D, however, a sample is presented below in Figure 25, showing the different conditions of each space within the journey. The analysis of all the journeys is shown in Appendix D.



Figure 24 JLT (top) and Greens (bottom) maps showing the journeys A, B, C, D, E and F used to conduct the interviews. Source: Google Earth extracted (2015).

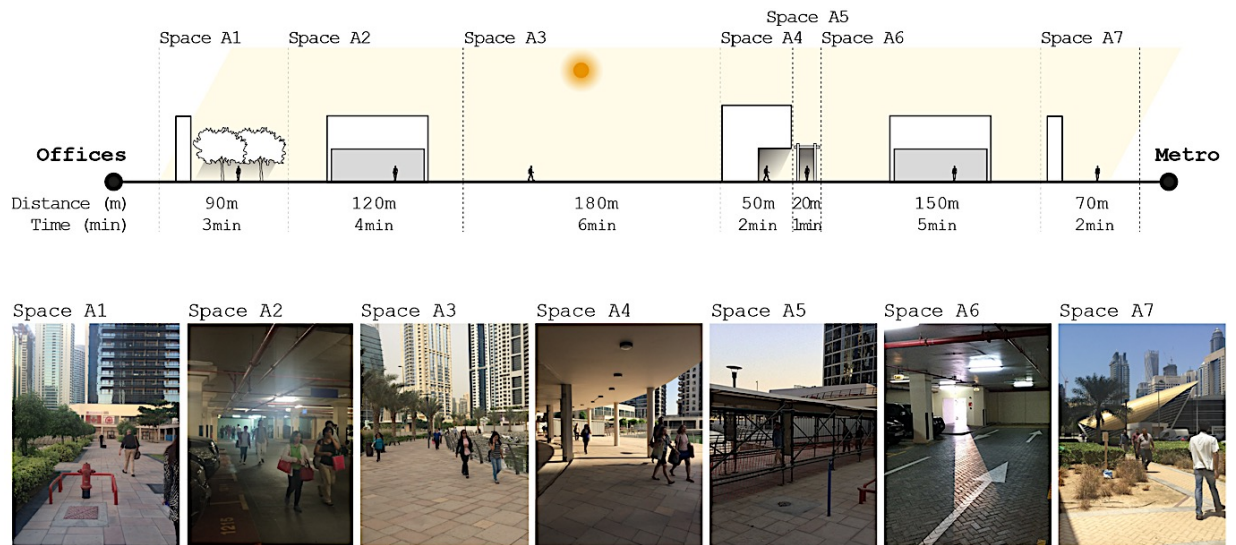


Figure 25 Sample of the analysis done showing the journey between the metro station and the offices.

Information about the subjects, such as their age, gender, clothing, duration of residence in Dubai and origin was gathered. Due to the wide thermal backgrounds of individuals in Dubai, the answers of the subjects who have been living there for less than six months were excluded, to reduce the subjectivity of votes by allowing time for acclimatization.

Subjective votes of thermal comfort (TCV) and thermal sensation (TSV) were noted on the ASHRAE scale: -3 cold, -2 cool, -1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, 3 hot, for the TSV and 1 very comfortable, 2 comfortable, 3 just comfortable, 4 just uncomfortable, 5 uncomfortable, 6 very uncomfortable, for the TCV. Alongside, the main meteorological parameters known to influence comfort in this region (T_a , V and RH) have been measured constantly using a 3 in 1 *testo* hand held anemometer with humidity measurement (see Appendix C). This allowed to quantify the votes gathered. All meteorological instruments used were selected in accordance with the specifications outlined in ASHRAE's Handbook of Fundamentals.

The measured climatic parameters T_a and RH were used to extract the mPET using RAYMAN. Clothing was set to 0.9 as a convenient average value for most pedestrians. Outcomes were then averaged and compared to PET values and the TSV gathered from the interviews. The scale used by Lin and Matzarakis (2008), which has been verified on the ASHRAE scale through many field surveys, providing a thermal sensation (TS) scale for people who lived in Taiwan, as a representatively subtropical climate, was calibrated against the actual votes from Dubai (see table 3).

Further questions were addressed such as ‘What bothers you most at this moment? Sun, heat, dust, etc.?’ and ‘How do you find the provision of shade along your journey?’ These were to capture people’s perception of their thermal environment. Besides, questions that verified the distances that people had walked, and the frequency of their walks throughout the year. People were also asked if they owned a car. All questions are shown in Appendix A.

4.4. Outcomes

The data and results from the fieldwork conducted was analysed carefully and findings were classified according to the aspects presented below:

4.4.1. Thermal sensation and thermal comfort

As it was important to set a comfort range from the data gathered, therefore the votes were clustered according to the ranges in table 3. Pedestrians voted that between 18° and 22°C they felt slightly cool, between 29° and 30°C they felt slightly warm and between 31° and 37°C they felt warm. The thermal neutrality votes were between 23° and 28°C. This range slightly extends above the range found in the previous studies by Lin and Matzarakis (2008). This is found to be reasonable in view of the high metabolic rates of the pedestrians where the former study involved subjects in steady conditions (refer to section 2.3.1. for steady and dynamic conditions). The mPET values revealed a steady increase compared to the actual TSV votes gathered during fieldwork (Figure 26), which suggests the sensitivity of pedestrians in Dubai to heat when compared to the Taiwanese votes used for mPET. Such suggestion agrees with the former study’s, investigating Taiwanese people, that they were highly tolerant of heat.

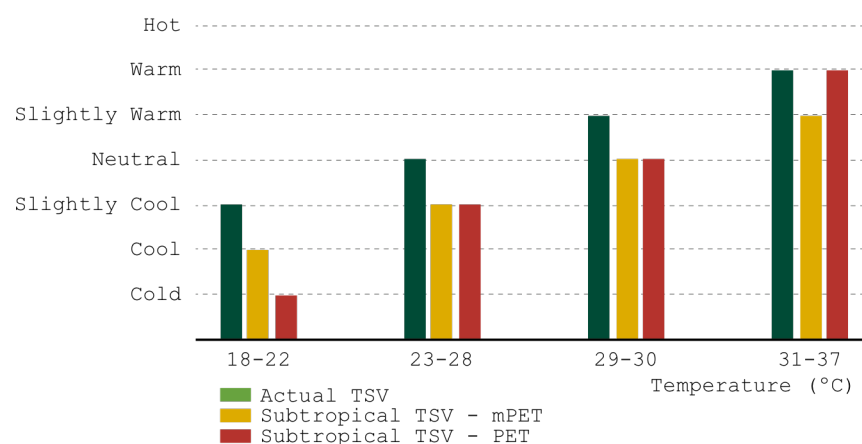


Figure 26 Diagram showing the average Actual Thermal Sensation votes compared to the PET and mPET extracted by RAYMAN

Pedestrians voted that between 18° and 19°C they felt just comfortable with the sensation of coolness; between 28° and 33°C they felt just comfortable but were just uncomfortable between 34° and 35°C and uncomfortable between 36° and 37°C (see Figure 27). The comfort range was in line with the votes of 'just comfortable', 'comfortable' and 'very comfortable' that were recorded between 18° and 30°C. At this range of comfort, pedestrians' TS ranged between slightly cool, neutral and slightly warm, which indicates that the interviewees were comfortable being slightly cool and slightly warm. The replies of 'very comfortable', 'comfortable' and 'just comfortable' was to lie within an acceptable range of comfort named the *tolerable* thermal comfort range, which is between 18° and 30°C. A wider range of comfort can involve the 'just uncomfortable' votes extending from 18° to 35°C. It is important to note that the wind variations were very small, on average 1.2m/s, had no significant influence on the TCV.

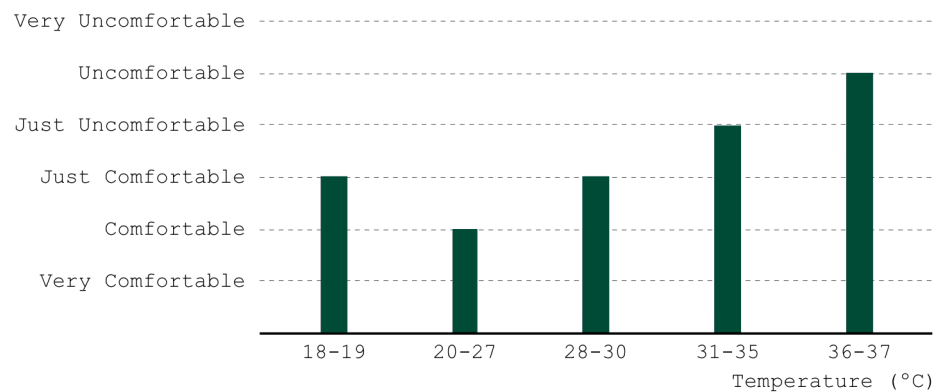


Figure 27 Bar chart that shows the TCV at different air temperature ranges

Further comparison between the TSV and the TCV (Figure 28) revealed that between 18° and 20°C pedestrians voted that they were just comfortable when they felt slightly cool. Between 21° and 23°C their thermal comfort improved to 'comfortable' while still being slightly cool. They still voted that they were comfortable between 24° and 26°C, even when their thermal sensation changed to neutral. Between 27° and 29°C TCV was 'just comfortable', while TSV remained neutral. The thermal sensation then jumped to warm between temperatures of 30°-32°C while the degree of comfort was voted to be 'just uncomfortable'. However, the warm sensation remained the same between 33° and 35°C and the comfort votes dropped to 'just uncomfortable'. Between 36° and 37°C, the highest temperatures covered during the interviews the warm sensation remained the same, but the thermal comfort reaction was 'uncomfortable'. This strange behaviour, where the thermal sensation remained the same between 30° and 37°C however, thermal comfort changed significantly, disallowed a relation between both votes to be seen.

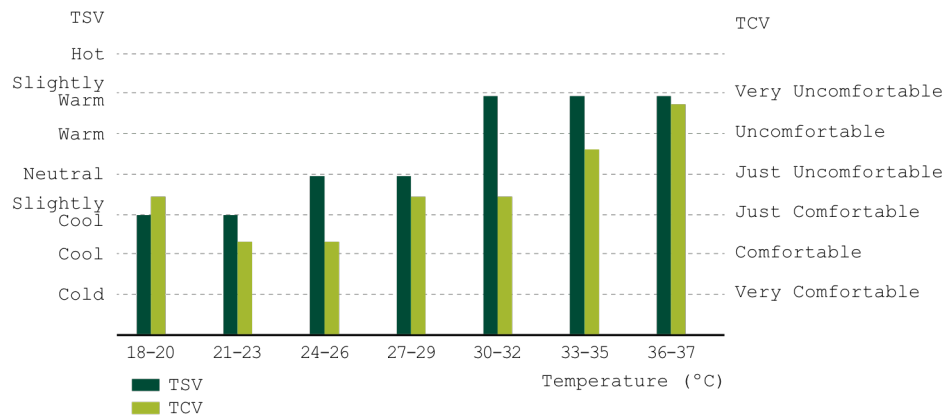


Figure 28 Bar chart that shows the TCV and the TSV at different air temperature ranges

A direct correlation was found between the actual TSV and the air temperature as shown in Figure 29. As the air temperature increased people's thermal sensation votes moved towards being hot. However, the few votes seen scattered away from such relation is due to the wide diversity of the subjects interviewed, which is the nature of the Dubai and due to the variations between the clothing values. For instance, two of the pedestrians interviewed along their way to work during midday in the mild period voted that they felt *hot* when $T_a = 25^\circ\text{C}$, $V = 1.2$ and $RH = 45\%$. The subjects were both from the UK and expressed their displeasure from the local climate as soon as they stopped for the interview. Both subjects wore full black suits, which also worsened their thermal sensation. On the contrary, other interviewees from Philippines, along the same trip voted that they felt *cold* during the same period, yet, in the morning time when $T_a = 19^\circ\text{C}$, $V = 1.3$ and $RH = 53\%$. Those subjects wore formal jackets but knee length skirts which has a lower clo value.

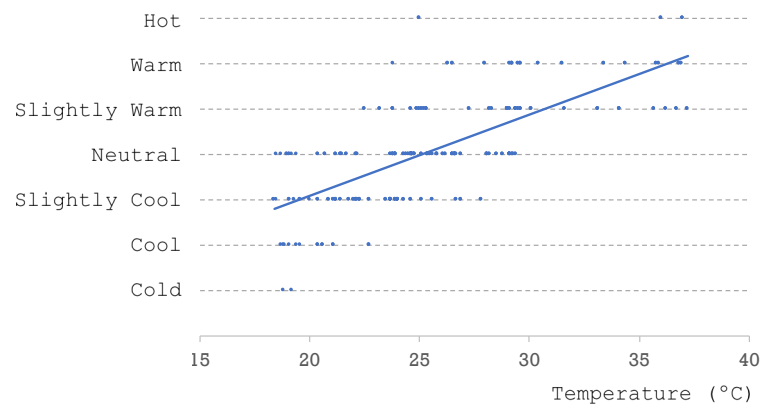


Figure 29 Scatter diagram showing the correlation of the actual TSV at different temperature ranges

It can be concluded that pedestrians felt neutral between 24° and 29°C and comfortable (votes of 'comfortable' and 'just comfortable') between 18° and 32°C. The interviewees were comfortable to be slightly cool or slightly warm. This demonstrates that the thermal comfort range is much wider than the thermal sensation range. The thermal sensation is a physiological process while comfort involves psychological parameters. This highlights the significance of the psychological parameter on people's thermal comfort outdoors, which was argued in the literature (section 2.2). However, it should be borne in mind that all previous votes presented took no account of the sequence of spaces that pedestrians have walked through or the shading conditions of these spaces.

4.4.2. Walking patterns and distances

On the route between the metro station and the office buildings, the flow of pedestrians was heaviest all the year round, Figure 30. Some of the pedestrians depended on the metro in their daily journeys. A few others also commented that the metro facility encouraged them to walk and depend less on their cars. Many expressed that if the shading provisions were designed to serve pedestrians better more people would walk. Therefore, it is notable that walkability did not, as some people argue, depend upon owning a car; in the present study, only 54% of the pedestrians interviewed had private cars. They mentioned that they walked only when the weather was pleasant and 68% of them chose not to walk in the summer (expressed as the period between May to November).



Figure 30 Pedestrians in JLT walking to work along the route from the metro station to the offices

The routes leading to the mosques in both urban districts were crowded with male pedestrians (for religious reasons), Figure 31, just before 1 pm on Fridays and there was a weaker flow at other prayer times throughout the day. The flow on Fridays at prayer time continued all year long, only slightly lessening during the hot period, regardless even of the lack of shade at various points on the route. This issue should be studied extensively to help planners understand the frequency of walking to and from different facilities when designing urban communities that promote walkability.



Figure 31 Image of male pedestrians walking from the mosque in JLT (left) and Greens (right) during noon prayer in May

The findings revealed that in mild conditions people chose shorter routes rather than shaded ones, but in warmer situations shaded routes were prioritized when they had the option. In JLT, on the route linking the metro station and office buildings, it was evident that most of the pedestrians used a short cut through a covered parking garage, Figure 32. This was a naturally ventilated semi-outdoor space. However, the space recorded higher air temperatures and higher humidity levels due to the heat dissipation from the cars together with the lack of ventilation. When they were asked, they said that this route was shorter and shaded. This revealed that people's perception of the thermal environment can be more influential than the thermal conditions of a space. It also revealed that pedestrians' perception of shaded spaces as cooler ones is higher as the weather gets warmer.

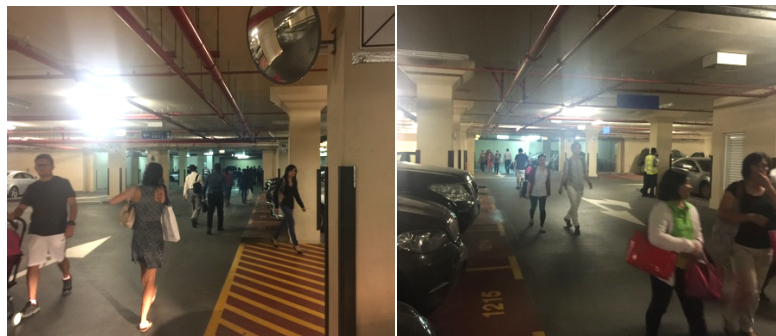


Figure 32 Image showing pedestrians walking through the parking spaces in JLT looking for both to shorten their routes and shade

The distances that people walked depended mainly upon the distance between the facilities. As the climatic conditions worsened, the frequency of pedestrians along the route went down but not the distances covered. Thus, in mild conditions the highest frequency of pedestrians along the routes investigated was seen in the mornings, midday periods and afternoons. During the warm period, the frequency during the morning and late afternoon slightly declined yet substantial numbers of pedestrians could still be seen. However, fewer of them were seen walking in the middle of the day.

In the hot period, the numbers of pedestrians reduced dramatically but a few could still be seen. These pedestrians mostly owned no car, implying that during the hot period people choose not to walk when they have an alternative, such as a car. The influence of the psychological factor ‘choice’ was deemed influential. When the TCV of people whom had, cars were analysed against those who didn’t, the perception of the microclimate of those who had cars during warm conditions was slightly better (one step on TCV scale), while people who were forced to walk were the most troubled by the weather.

When the walking speed of scores of the interviewed pedestrians in the two communities was measured, it was found that they walked on average at a speed of 1.5 m/s. It should be noted that they walked to certain destinations, quite unlike those who were clearly walking for leisure, at 1.1 m/s. In this study, however, people’s walking distances were measured by time in minutes, since the time of exposure that pedestrians can tolerate in a warm or hot environment can be more indicative of the heat stress on their body than of the distance covered.

The surveys revealed that pedestrians walked for a great deal of the year in both the urban communities surveyed. 61% of the pedestrians mentioned that they walked along the same route all year round, while 36% admitted that they avoided walking in summer (Figure 33). Pedestrians who did not walk regularly accounted for only 3% and those who rarely walked for only 1%. It should be borne in mind that the sample surveyed only people who had chosen to accept the conditions and walk outdoors at the time, which influences their satisfaction. Although the findings were not classified according to the climatic period, it is noteworthy that, as the weather got warmer, the longer routes linking facilities were less occupied than they were during the mild period.

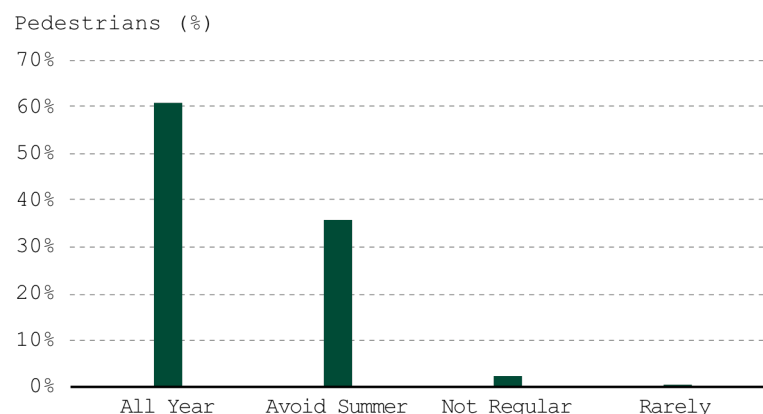


Figure 33 Bar chart that shows the walking frequencies of the pedestrian’s votes

The distances that people walked depended mainly upon the distance between the facilities. It was observed that as the climatic conditions worsened the frequency of pedestrians along the route was reduced, but not the distance by which people shortened their route. So, in mild conditions the highest frequency of pedestrians was seen along all the routes investigated in the morning, midday and late afternoon periods. In warmer weather, the frequency in the mornings and late afternoons was slightly reduced yet pedestrians could still be seen in considerable number. However, fewer of them were seen in the midday period.

29% of pedestrians walked for between 6 and 8 minutes, while 28% walked for 9-11 minutes. Only 6% of pedestrians walked for between 1 and 2 minutes, 9% from 12-14 minutes and 2% walked for more than 15 minutes (Figure 34). Most pedestrians walked between 3 and 11 minutes, covering approximately 100-330m at an average walking speed of 3.3 m/s.

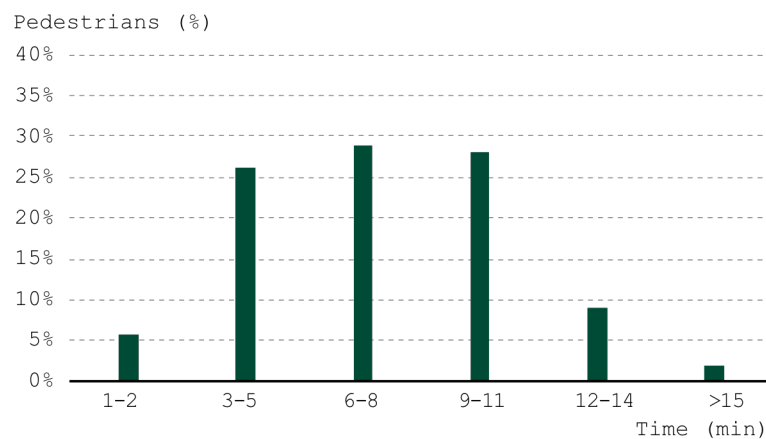


Figure 34 Bar chart that shows the percentages of pedestrians walking distances

4.4.3. Influence of thermal transitions

Pedestrians endure thermal transitions – shifts in the thermal conditions – as they pass through different spaces in their walks. In this research, thermal transitions are anticipated in conjunction with physical changes within a space, which lead to a change in the thermal conditions. Therefore, those who walk along a space where the same physical attributes and geometry are maintained do not experience thermal transitions.

The findings revealed that in all climatic periods shaded spaces provided better comfort conditions for pedestrians than non-shaded ones did. When the interviews were conducted immediately after a transition to a shaded space, or after a couple of minutes spent walking in the shade, the changes in pedestrians' thermal comfort were more sensitive to the thermal transitions than their thermal

sensation was. However, when the microclimatic parameters were within the comfort range, moving from a shaded to a non-shaded space did not influence thermal comfort and thermal sensation negatively. Yet, in the warm period during midday and all day in the hot period, pedestrians' thermal sensation worsened one and two steps when moving from the shade to the sun.

Moving from indoors to outdoor space influenced pedestrians in different ways, depending upon the shading provision of the outdoor space. When people were interviewed after they had left the mosque and the metro station (air-conditioned), their thermal votes differed, though both groups were interviewed at the same time of day and in the same climatic period. The metro station exit was followed by shaded space, while the exit from the mosques in both districts had no adjacent shade. However, along the three routes pedestrians had spent more than 10 minutes indoors.

During the mild period the TSV were similar when pedestrians went from indoors to a shaded or non-shaded space. However, in warm and hot conditions, their thermal votes changed for the worse, to being warm and hot when the building opened on a non-shaded space. This effect intensified at midday. It was proved that the length of exposure that pedestrians endure in a space influenced their sensation more strongly than the thermal conditions of the space. When pedestrians took a short walk through a non-shaded space, their TCV did not change, but their TSV did.

The findings also revealed that the same spaces influenced the pedestrians differently, depending on direction in which they walked. Because the sequence of the spaces that they were exposed to was different. Interviews in a non-shaded space showed that people who came from a shaded space voted that they felt 'slightly warm' while others who had come from the opposite direction and from a non-shaded space voted 'warm'. This highlights the importance of considering the direction of the flow of people, particularly the antecedent space, when designing utilitarian routes.

JLT had a sunny space on the journey between the metro station and the office buildings (Figure 35), which many crossed between 8:00 and 9:00 and between 16:00 and 17:00. Space providing no means of solar protection has been identified as the most uncomfortable space in the morning surveys. The reason is partly attributable to the sequence of sun and shade leading to this space, where people have been walking for 7 minutes at least and have started to experience thermal discomfort.

Few pedestrians assured that this part of the route was the main or only reason for them to stop using this route in the warm season. Interviews conducted in this space revealed one step in the sensation vote above the other spaces at the same time of day. A few pedestrians complained that this space put them under heat stress for the rest of their journey, even when they had moved to a shady zone.

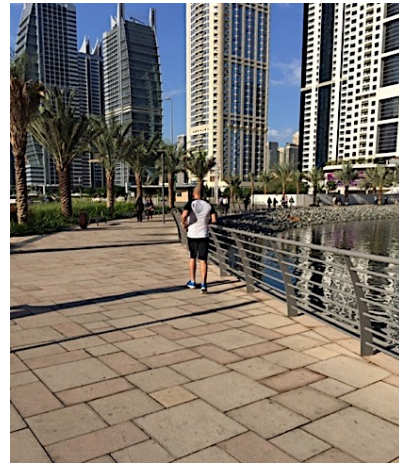


Figure 35 The sunny pathway in JLT district that pedestrians complained that it lacks comfort

4.4.4. Perception of shade and comfort

Pedestrians normally detest deviating from the most direct and shortest path and the impact of microclimate on their routing choice is traceable only if the “climate-optimized” route is slightly longer than the shortest possible one or in extreme climate conditions (Bruse, 2007). But if we think of an urban open space as a location that offers more options than traffic distribution alone, the impact of microclimate can become much larger and more visible.

In JLT, most of the pedestrians walking between the metro station and the offices took a short cut through the parking garages, Figure 32. These spaces were shaded, however, becoming warmer and more humid in the mild, warm and hot periods by 4 K, 7 K and 2 K, respectively. This was due to the lack of ventilation and the heat dissipated from the cars. When pedestrians were asked why they took this path and avoided walking along the more pleasant path beside the lake, they replied that this shortcut was both shorter and shaded. Some answered that they were not sure it was cooler, but that solar protection is important. This finding reveals that thermal comfort seems more important and attractive than visual comfort.

Most shaded spaces were not necessarily cooler at different times of day, given the mean radiant temperature and the lack of ventilation. However, it can be generalized that all pedestrians preferred shaded spaces and perceived them to be cooler. Yet, when they were asked if the shading provision along their paths were sufficient or not, they responded differently. 54% mentioned that shade was not enough, noting that the routes they had selected were more pedestrian-friendly than many other areas in the city.

People's perception of the microclimatic parameters was investigated by asking them whether sun heat, dust, lack of wind or the humidity was the source of greatest discomfort on their walk. Almost half the interviewees in the warm and hot periods voted that sun heat was the most uncomfortable, Figure 36. In the hot period, the humidity was the only other parameter causing discomfort. As the climatic period improves the discomfort caused by humidity is reduced. In the warm period, almost half the pedestrians were bothered by none of the parameters mentioned. Only during the mild period were most pedestrians were very satisfied with the weather and not troubled by something.

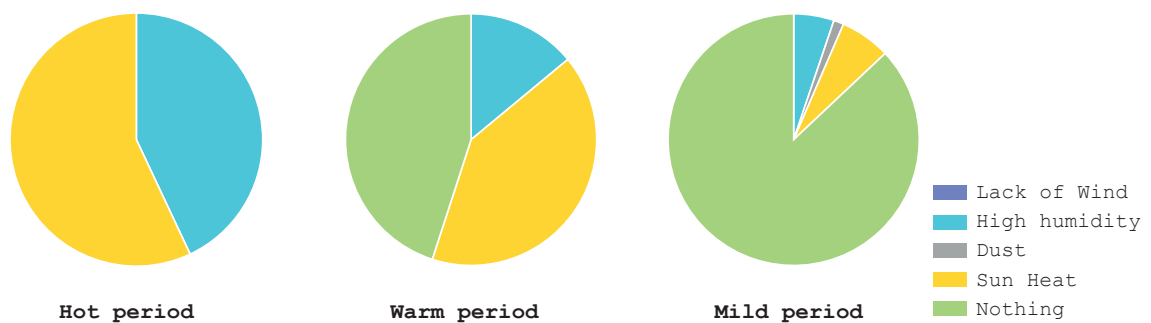


Figure 36 Charts showing the percentages of pedestrians votes at the three climatic periods when asked about the most bothering parameter.

It was also found that, in the mild conditions pedestrians enjoyed walking outdoors, regardless of the shading provision. In both communities, people walked to schools, mosques, their work and the metro at different times of the day. In the early morning, the average air temperature is around 19°C and pedestrians adjust their clothing to feel 'comfortable'. However, they voted that they felt 'slightly cool' and 'cool', with thermal comfort levels of 'comfortable', which confirms that people felt comfortable feeling slightly cool. This cool sensation was felt along the fully shaded path, Figure 37. However, a few pedestrians avoided the shaded paths when the wind blew above 1.7m/s.



Figure 37 Images of the pedestrians walking to school along the shaded path in Greens district during the morning.

4.4.5. Other factors

The interviews were conducted with the aim of understanding what adaptive measures could be taken by the wide background disparities of pedestrians in this climate. It was found that most pedestrians in Dubai wear more clothing than their counterparts in many hot cities. Many of the pedestrians, moreover, wore a suit, since they were on their way to or from work. Others were going to the mosque, which necessitates wearing long pants and half sleeves. Percentages for the different clothing levels are seen in the diagram below (Figure 38). This highlights the need to provide cooler outdoor conditions for people here than for many elsewhere who live in the same climate.

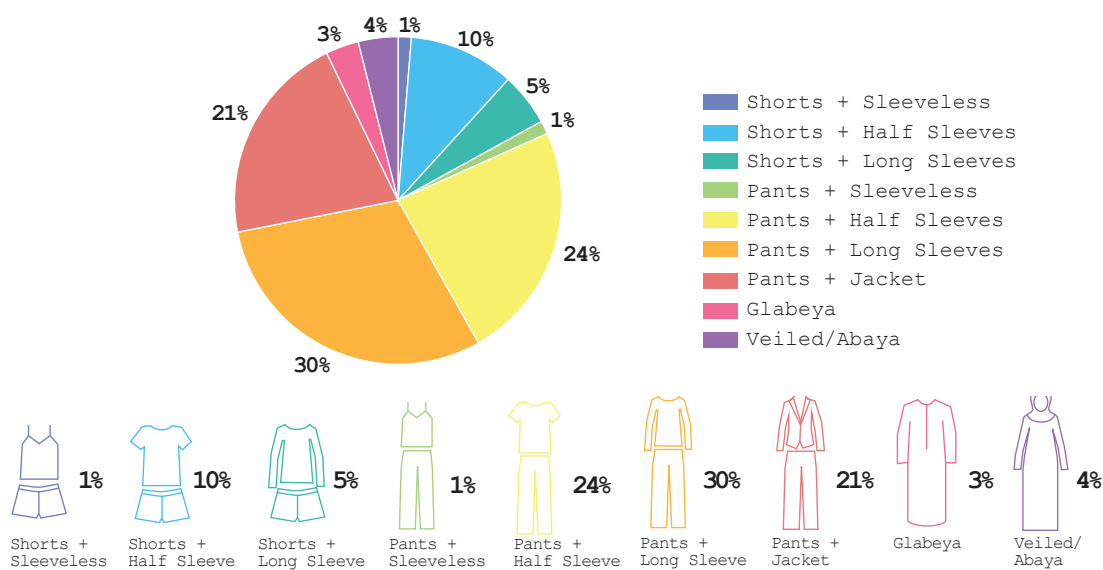


Figure 38 Diagram showing the percentages of clothing worn by the people interviewed.

With other adaptive measures taken, only 17% of the interviewees mentioned that they sometimes used an umbrella for shade. 4% wore sunglasses, 6% wore a hat and only 4% mentioned that they would consider taking water/a cold drink. 3% said that they would use a hand-held fan if it was available. Most people (66%) replied that they took no measures at all, asserting that it was impractical to carry anything. Therefore, shade ought to be provided by the environment rather than depending on adaptive behaviours.

4.5. Conclusion

Findings from the interviews conducted helped understand multiple aspects about the nature and preferences of pedestrians walking along utilitarian trips in urban communities in Dubai. It can be concluded that, in the mild season (December-January) pedestrians enjoy walking outdoors even at midday. This period proved to provide comfort for a wide number of pedestrians, despite the lack of shade.

Observations revealed that most pedestrians in Dubai have higher clothing values compared to many hot cities, which reduces the evaporative losses from the skin surfaces thus reducing comfort. For this reason, higher wind speeds are required in order to improve thermal sensation and thermal comfort. Pedestrians voted that they were 'comfortable' when they felt 'slightly cool', which conforms with findings from Zhang (2003) that feel comfortable being slightly cool. In other periods of the year the discomfort endured depends upon the microclimatic conditions provided by the built environment such as shade and wind. Pedestrians along utilitarian trips have a high tolerance of heat and were found to walk during long periods of the year, avoiding non-shaded routes.

Shaded spaces are perceived to be cooler, even when the thermal conditions are equivalent or worse than non-shaded ones. The influence of the psychological parameters was dominant. People who had choice not to walk and use their cars had higher levels of satisfaction with the weather compared to those who were obliged to walk. In general, in thermal conditions closer to the comfort zone, most pedestrians do not recognize changes within the thermal environment. There is a direct correlation between mPET votes (predicted by RAYMAN) and the actual TSV with a steady increase in the actual votes. This was due to the difference in the activity level between both as the metabolic rate. Thermal neutrality was achieved between 23° and 28°C and thermal comfort between 18°C and 32°C.

The thermal comfort range is wider than the thermal sensation range due to the influence of the psychological parameter on people's tolerance outdoors. The duration of exposure is more influential on their sensation more than the thermal conditions of the space, where pedestrians were not bothered by walking through non-shaded spaces for a short time. In other words, instant changes in the TSV, as people walk in the non-shaded space will not influence the TCV when for a short duration.

CHAPTER 5: Social Surveys 02: Thermal Walks

The way in which pedestrians experience the thermal environment outdoors is based largely on the sensory cues that they pick up as they move through the urban continuum (Middleton, 2010). Previous studies of thermal sensation and perception have tended to focus on the microclimatic conditions prevailing in a set of different spaces that may be in the same urban quarter or area, but are usually discontinuous, located in separate areas, or of a certain typology. In a comparative analysis of the thermal experience across a range of urban spaces, dynamic variations in thermal comfort are found as pedestrians move. generally pedestrians are able to perceive and consciously identify variations in the microclimatic conditions (Vasilikou and Nikolopoulou, 2014).

Thermal walks employ a sense-walking technique that analyses the urban climate, the morphology of spaces and the way that people perceive their combined effect, through a series of structured walks with simultaneous environmental and human monitoring. This process, introduced by (Vasilikou and Nikolopoulou, 2015, 2014, 2013), is based on point-to-point evaluations of thermal perceptions and spatial variations. Its special feature is the combination of objective microclimatic and spatial data with subjective responses by pedestrians on the street.

5.1. The context

The study was conducted in the urban district Jumeirah Lakes Towers (JLT) introduced in the previously (section 4.1.1). A typical sunny outdoor path with minimal flow of people was selected to conduct the experiment. The path had no obstructing elements or trees to avoid influences from aspects other than those structured in the experiment. It is adjacent to an exit from the (air-conditioned) building on the podium level. The ground was covered in a mixture of light-grey concrete tiles and brown interlock tiles with no vegetation or shading elements (Figure 39). The space had a linear shade, which came from the building mass. The path provided similar physical space conditions to those investigated in Chapter 4 and seen in many urban communities.



Figure 39 Images showing the space used to conduct the thermal walks experiment.

5.2. Aim

The methodology was developed to understand how the changes between interconnected spaces may affect pedestrians' thermal perception and thermal comfort. The goal was to identify the duration pedestrians could tolerate walking outdoors in each climatic period and under different microclimatic conditions. Besides, the experiment aimed to investigate the influence of thermal transitions such as that between the indoor and the outdoor, and between shaded and non-shaded spaces.

5.3. Process description

5.3.1. Short walks

A series of short walks were observed at different times of the year. The study involved six healthy participants of similar age (average of 34) and body mass index (average of 25.6) (see Table 4). Each test represented a complete twenty-minute walking period (Figure 40). Each subject was tested on a separate day each month. A total of 18 walks were conducted throughout the year, with three walks per each participant. The walking speed was averaged at 1.8m/s; the speed at which pedestrians took the utilitarian journeys investigated during the fieldwork presented in Chapter 4.

Before each session, the subjects spent twenty minutes on adaptive pre-conditioning and to let them reset their body temperatures. During the walk, the subject was asked to leave the building and walk along the path for 15 minutes (Figure 40). The TSV and TCV were recorded manually on a sheet once every minute while the walk continued (Figure 41). The subject was then asked to shift to the shaded area where an air velocity of 3.2m/s was induced by means of a hand-held fan directed toward the

face and upper body. The subjects continued walking for another four minutes in the shade before moving back to the sun for one more minute with the air velocity maintained at 3.2m/s (Figure 40).

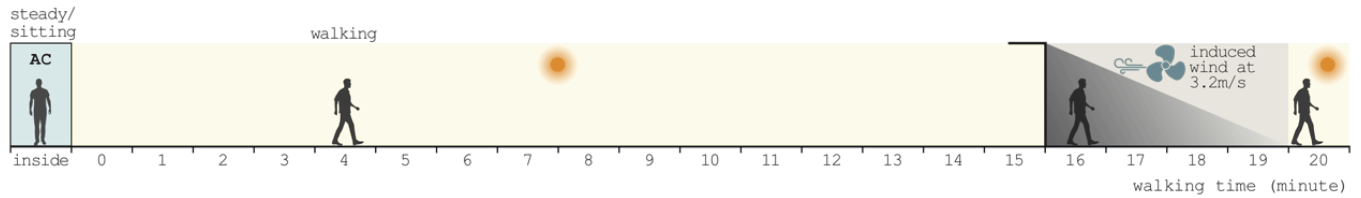


Figure 40 Diagram showing the thermal transitions that the subjects were exposed to during the 20 min of the thermal walk experiment.

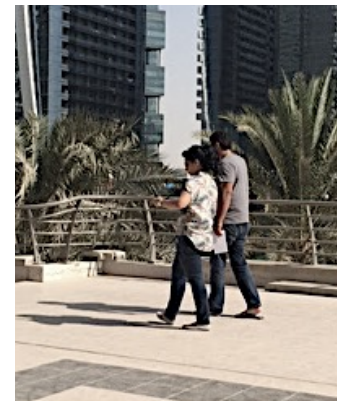


Figure 41 Image of one of the thermal walks conducted

The study took place at the same time each day (13:00-14:00) over six consecutive days in each of three months (January, May and November) representing the mild, hot and warm periods of the year, respectively. The subjects were asked to vote the numerical value along the TSV and TCV scale cards they held.

5.3.2. The subjects

Six subjects, 3 females and 3 males, volunteered to participate in the thermal walk. These participants were all acclimatized to the local weather conditions, having lived in Dubai for more than two years. The same six subjects were tested repeatedly in January, May and November recording a total of 18 walks throughout the year. Table 4, shows the key data for each subject and his/her origin. The subjects had different thermal backgrounds mostly representative of the most dominant nationalities observed in the communities where the interviews were conducted and presented in Chapter 4.

Table 4 Shows personal information about the six participants involved during the thermal walks

ID	Gender	Age	BMI	Lived in Dubai	Origin
1	Male	34	26.2	7 years 3 months	Egypt
2	Female	32	25.2	2 years 6 months	India
3	Male	36	26.8	3 years 2 months	Iraq
4	Male	35	26.6	5 years 3 months	Syria
5	Female	31	24.6	3 years 6 months	Egypt
6	Female	34	24.1	5 years 10 months	Philippine

Before the experiment, we ascertained the clothing preferences of all the subjects. It was intended to allow them to walk comfortably and have a sense of control, which would influence the level of their thermal comfort. During all the walks, the subjects wore light coloured cotton T-shirts with half sleeves, long jeans pants and closed shoes (clo value 0.7). This clothing typology was that considered most likely by pedestrians in this region. In the January tests (mild conditions), all the subjects wore cotton socks as well, while in November and May (warm and hot conditions), both males and females wore sandals, which exposed their feet during the walks. All the subjects preferred to, and did, wear sunglasses in the tests.

5.3.3. Measuring skin temperature and monitoring sweat rate

Skin temperatures were collected each minute, using a handheld Fluke 561 infrared thermometer (accuracy of $\pm 1^{\circ}\text{C}$; operating temperature range of $0^{\circ}\text{--}50^{\circ}\text{C}$). The tool was held at a distance of 300 mm from the target, resulting in a spot size of 38 mm. Skin temperatures of both face and hands were measured to indicate the physiological response of the subjects' bodies to walking and to solar exposure. The clothing that the subjects had worn during the walks typically exposed their faces and hands, which was similar to pedestrians in this climate as explained in Chapter 5.

The skin temperature of the forehead was measured in the survey because it has been identified as accurate in representing the core temperature so long as a 2°C compensation is included (Sessler, 2008). The skin temperature on the dorsal surface of the left and right hands and averaged. To minimize the risk of heat gain at these areas, participants were instructed not to touch the measured skin surface points or wipe the sweat (if any) throughout the experiment period.

Sweat observation was included in this study as an indicator of the physiological thermal stress that the body suffers while walking. Since most body parts are covered by clothing, facial sweat was the only indicator for such stress. An observation method was followed, dividing the sweat rate for the subjects into three possible categories, low, medium or high sweat. 'Low sweat' indicates a mild

moisture level on the skin surface, while 'high sweat' reveals excess moisture on the skin in the form of water droplets.

5.3.4. Environmental monitoring

Spot measurements were conducted during each walk using the hand-held 3 in 1 *testo* anemometer that also measures humidity (Appendix C). The three environmental parameters, T_a , RH and V were measured every minute and recorded manually on a notepad along each walk.

5.4. Outcomes

The empirical data gathered from the six subjects were averaged each month (climatic period) and the findings are presented below.

5.4.1. Transition between indoors and outdoors

The measurements taken showed that the indoor temperatures were very similar during the three periods: between 24.1°C and 24.7°C, which is typical for the buildings of Dubai. Such conditions provided comfort and thermal neutrality only during the hot period. The air temperature difference between indoors and outdoors during the hot, warm and mild periods was 15K, 13.3K and 8.4K respectively. Immediately after the subjects were exposed to such difference in air temperature, their TSV changed.

During the mild period TSV increased by one step on the voting scale and during the warm and hot periods by two steps (Figure 42). There is a strong direct relation between thermal distance and the thermal sensation, whereas the thermal distance increases, changes in thermal sensation becomes more intense. Such relation is dependent upon the climatic period, which defies whether the step changes move towards thermal neutrality or not. This is clearly seen in Figure 42, between the inside and minute 0. Furthermore, as the outdoor temperatures increases during the hot period, the thermal gap between indoor air-conditioned spaces and outdoor spaces increases. However, the number of step changes in TSV and TCV is different depending on the direction of movement – from indoor to outdoor or opposite. This was observed after the thermal walks ended and the subjects moved to the same indoor air-conditioned space they initially started from. These observations were not recorded due to the lack of consistency in the experimental conditions at all times when the experiments were conducted.

5.4.2. The walking distances

Findings revealed that the subjects were able to walk for 8 minutes during the hot period and 10 minutes during the warm and mild periods, stating that they were 'comfortable' and 'just comfortable', Figure 42. Furthermore, during the hot and warm periods the subjects were able to walk for 3 extra minutes and felt 'warm' but still 'just uncomfortable'. However, during the mild period this was reduced to 1 minute only, which means that they had a higher tolerance of the sensation of warmth when the temperature was higher. This was consistent along all six participants.

Such correlation indicates that when evaluating thermal comfort, psychological parameters such as expectation cannot be ignored, and thermal sensation does more than sufficient indicate subjects' satisfaction with their surroundings. This view is supported by the fact that the subjects denied feeling 'very uncomfortable' even after walking for 20 min during the hot period, Figure 42. When they were asked to confirm the lack of such vote (very uncomfortable) they justified that they could still tolerate discomfort for the remaining time of the walk. This revealed that because they knew that the experiment was about to end increased their acceptance to the conditions. Such finding highlights that people's acceptance to warmer spaces increases towards the end of the journeys if they know that they are approaching their destination.

Thermal sensation escalated faster when the air temperature was higher during warmer conditions. The subjects endured a 'slightly warm' feeling for only 3 minutes in the mild period and 2 minutes in the warm period, Figure 42. This vote was completely omitted during the hot period. The subjects tolerated walking for 4 minutes during the hot period, 7 minutes during the warm period and 9 minutes during the mild period, feeling something between 'slightly warm' and 'warm'. From this it is clear that in hot conditions step changes in a pedestrian's thermal sensation take place before discomfort is triggered. In this study, changes in TSV were more sensitive (faster) to the thermal environment than changes in TCV.

Generally, when observing the TCV bars (indicated as black dotted arrows) in Figure 42 to compare the patterns of thermal comfort along the distances travelled during the three periods, it can be noted that differences between the mild and warm period are small compared to the hot period. The small differences during the mild and warm period recorded similar patterns during the shaded and non-shaded parts. Noting that these experiments were conducted during midday, it assures the possibility of potential improvements in pedestrian's comfort during the warm period if suitable measures were taken. However, the TSV changes seen Figure 42, shows the higher response of TSV compared to TCV, which has been discussed previously.

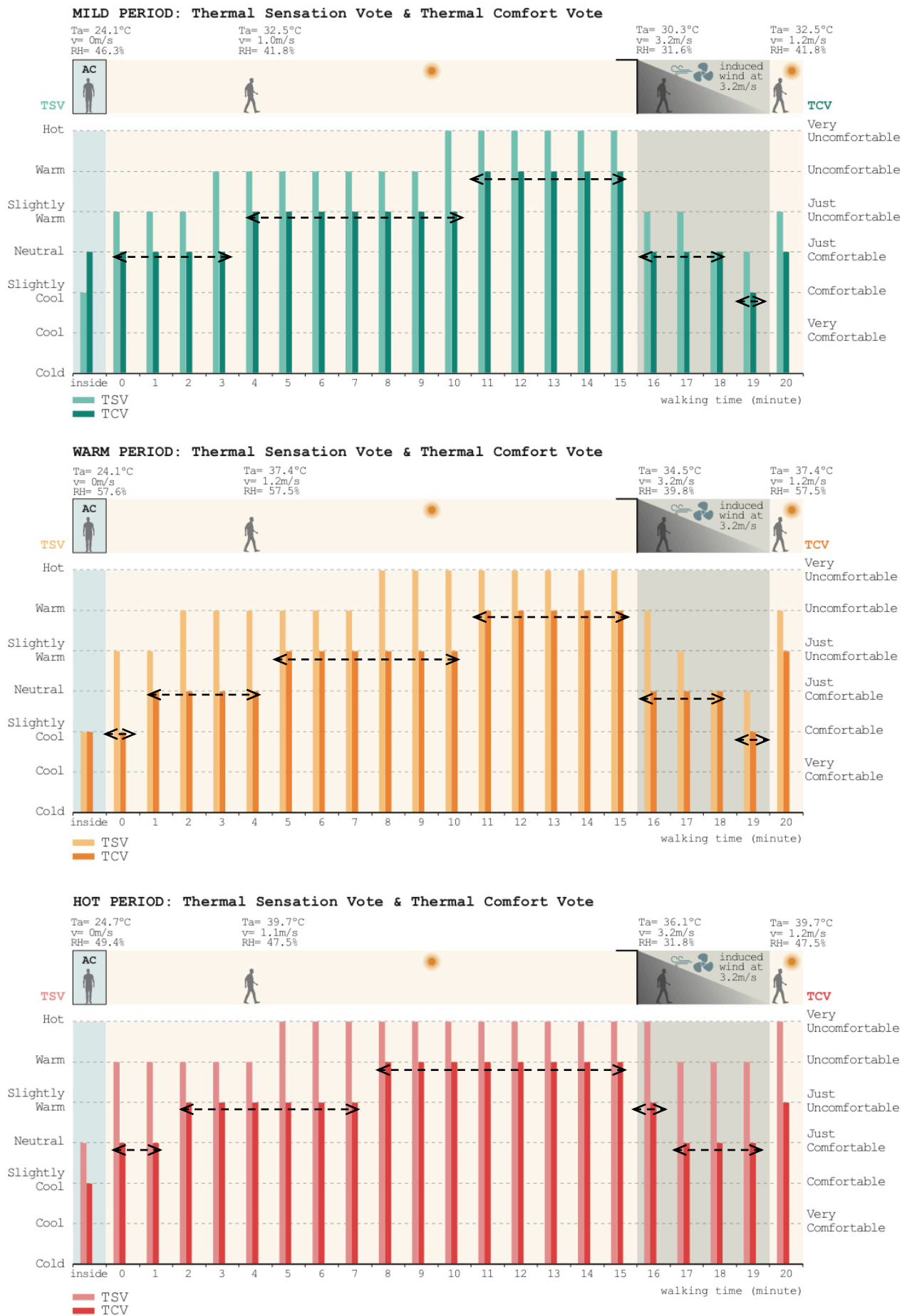


Figure 42 Diagram showing the relation between the TSV and TCV for the three climatic pods

5.4.3. The influence of shade and wind

Direct solar radiation has been shown to influence the human body. It was observed that during the walks, when the subjects had to turn to go back to the start point, the subjects felt better when they were facing the sun or had their backs to the sun. This was directly influenced by the exposure of the face to the sun.

As the subjects moved into the shade, the space was cooler by 3.6K, 2.9K and 2.2K during the hot, warm and mild periods respectively, where the cooling effectiveness of the shade increased as the conditions got warmer (Table 5). However, shade and wind improved the TCV instantly more than the TSV (Figure 42) due to the removal of the large amount of solar radiation.

Table 5 Differences between average Ta and average V between the shaded and non-shaded space during the mild, warm and hot periods. The TSV and TCV are after spending 4 min post transition.

Period	ΔT_a (°C)	ΔV m/s	TSV	TCV
Mild	2.2	2.1	Warm	Just Comfortable
Warm	2.9	2.0	Neutral	Comfortable
Hot	3.6	2.2	Warm	Just Comfortable

On the one hand, the instant influence of solar protection and wind on TSV meant that no improvement occurred during the hot period, while during the mild and warm periods TSV improved by one step (Figure 42). This revealed a relationship between the duration of exposure to heat and the step changes in TSV, whereby the longer the subjects endured heat, the more time was required for them to cool down. This pinpoints that the presence of small shaded areas – i.e. single trees or shading elements – in an urban environment will have only an insignificant influence on pedestrians' thermal sensation.

The overall TSV along the transition improved by three steps from 'hot' to 'neutral' during the warm period, two steps from 'hot' to 'slightly warm' during the mild period and one step from 'hot' to 'warm' in the hot period. The influence of solar protection and wind movement on TSV was strongest during the warm period. It was noticeable that the subjects who sweated most could cool down instantly when exposed to wind. This is due to the evaporative heat losses occurring alongside the skin, reducing its temperature, thus cooling the body.

At the same time, as the subjects moved into shade, their TCV improved instantly, by one step on the voting scale in the hot period and two steps in the warm and mild periods. It was also observed that

comfort was regained throughout all three climatic periods. Moreover, 4 minutes of solar protection and a wind speed of 3.2m/s improved TCV by two steps during the hot period and by three steps during the mild and warm periods (Figure 42). When the sweat rate was higher, the wind had a stronger capacity to improve thermal sensation. This skin cooling effect improved thermal comfort instantly.

It is noteworthy that to begin with wind speeds of 1.2m/s and 2.2m/s were separately tested to identify a reasonable value for planners to use. All the responses substantiated the finding that a wind speed of 3.2 m/s was the lowest that would improve the thermal sensation. However, it should be noted that the wind induced during this experiment was accompanied by a transition to shade.

When considering only the influence of shade on pedestrians' thermal sensation votes it is worth noting that during the mild period the TSV was two steps higher between the shaded and sunny spaces (slightly warm to hot) and the TCV was also two steps higher between the shaded and sunny spaces (just comfortable to uncomfortable) (Figure 42).

During the hot period the TSV was one step higher between the shaded and sunny spaces (warm to hot) and the TCV was also two steps higher between the shaded and sunny spaces (just comfortable to uncomfortable). During the warm period the TSV was three steps higher between the shaded and sunny spaces (neutral to hot) and the TCV was also three steps higher between the shaded and sunny spaces (comfortable to uncomfortable).

5.4.4. Moving back to the sun

As the subjects moved back into the sun after 19 minutes of walking, their TSV shifted instantly two steps from 'neutral' to 'warm' during the warm period; one step from 'slightly warm' to 'warm' during the mild period; and from 'warm' to 'hot' during the hot period (Figure 42). The most significant regression in TSV and TCV was recorded in the warm period, which was also the period recording the highest improvements upon moving into the shade. Therefore, it is important to ask whether the level of improvement in thermal sensation achieved in a particular space would be maintained when moving out of the space. This requires further testing.

5.4.5. Skin temperature

When the skin temperature was measured during the walks, the aim was to find a relation between it and the microclimatic conditions and verify whether it could be indicative to the TSV at different times of the year. Finding such relation was intended to verify the thermal sensation values at the later stage of this research.

Observing Figure 43, the comparison between the Tsk during the three periods revealed that the highest values was during the warm period, followed by the hot and mild period consecutively. This was during the walk along the non-shaded space. This was justified due to the presence of larger amount of sweat on the skin areas measured during the hot period more than that present the warm period, which cooled Tsk relatively (Figure 43). However, during the 4 minutes' walk along the shaded space the Tsk values were highest during the hot period, followed by the warm and mild period consecutively. Which proves that shade was effective to improve Tsk in the warm period compared to the hot period (Figure 43).

During the three periods, a direct correlation between Tsk and Ta was found, while an inverse relation was found with RH (Figure 43). The relation between the Tsk and the relative humidity was stronger than that with the air temperature. This is applicable in hot climates where the cooling factor of sweat cannot be ignored. Therefore, Tsk can be considered to be dependent on the skin wettedness as a necessary factor to be considered. Also, Tsk was slightly influenced by the thermal transitions, yet, significant changes required more time to take place. Figure 44, shows that the transition between indoor to the outdoor was most influential to increase Tsk, between the inside and minute 0. During this transition, the rise in Tsk was highest during the hot period followed by the warm period and the mild period. It can be concluded that as the thermal distance increases, changes in Tsk increases. This was also verified at the transition between the non-shaded and shaded space, at minute 16. Therefore, Tsk can be used to indicate the thermal transitions.

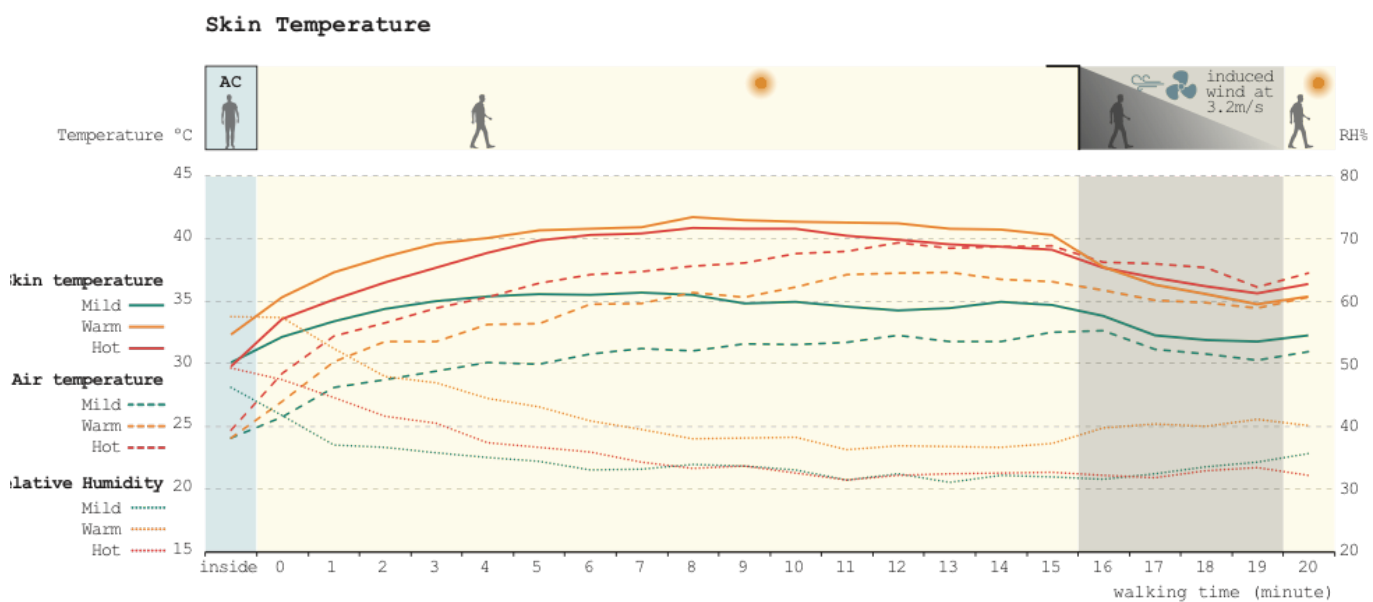


Figure 43 Graph showing the averaged air temperature, relative humidity and skin temperature for all the subjects during the thermal walks

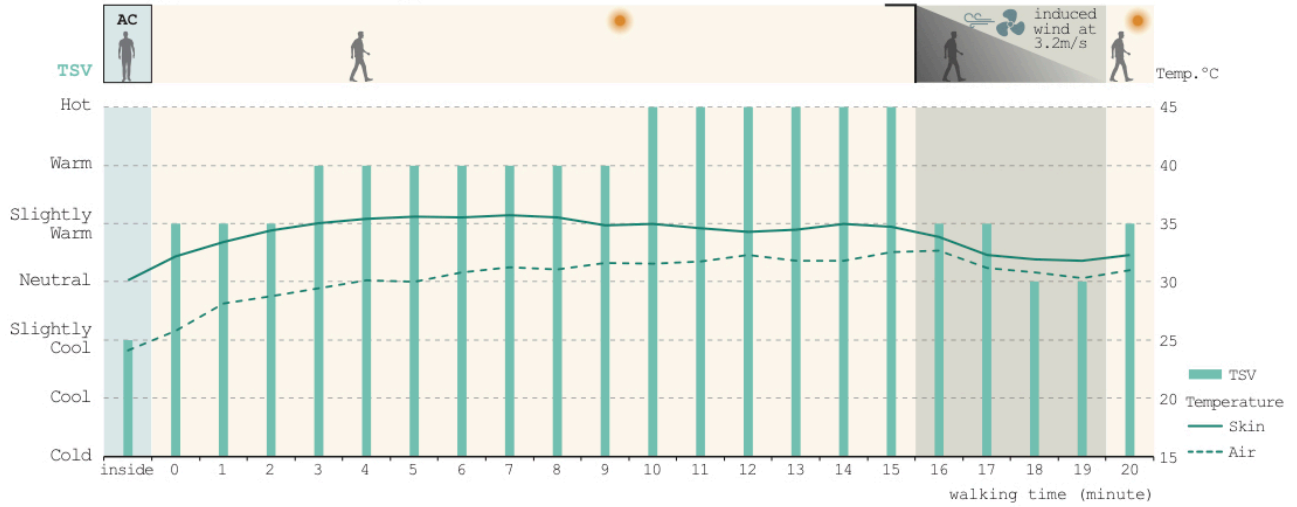
MILD PERIOD: Thermal Sensation Vote & Skin Temperature

Ta= 24.1°C
v= 0m/s
RH= 46.3%

Ta= 32.5°C
v= 1.0m/s
RH= 41.8%

Ta= 30.3°C
v= 3.2m/s
RH= 31.6%

Ta= 32.5°C
v= 1.2m/s
RH= 41.8%



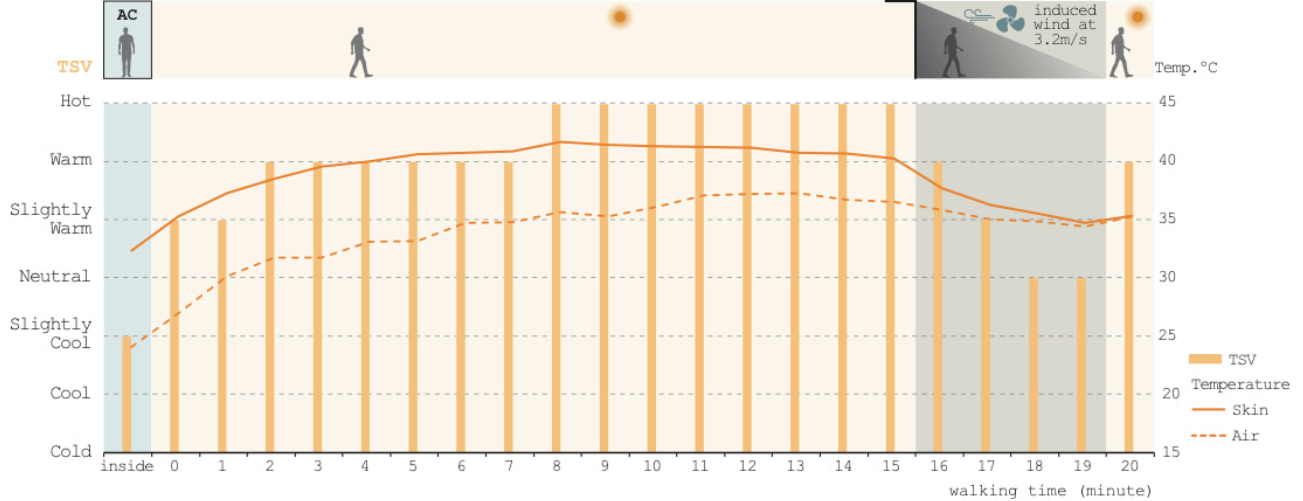
WARM PERIOD: Thermal Sensation Vote & Skin Temperature

Ta= 24.1°C
v= 0m/s
RH= 57.6%

Ta= 37.4°C
v= 1.2m/s
RH= 57.5%

Ta= 34.5°C
v= 3.2m/s
RH= 39.8%

Ta= 37.4°C
v= 1.2m/s
RH= 57.5%



HOT PERIOD: Thermal Sensation Vote & Skin Temperature

Ta= 24.7°C
v= 0m/s
RH= 49.4%

Ta= 39.7°C
v= 1.1m/s
RH= 47.5%

Ta= 36.1°C
v= 3.2m/s
RH= 31.8%

Ta= 39.7°C
v= 1.2m/s
RH= 47.5%

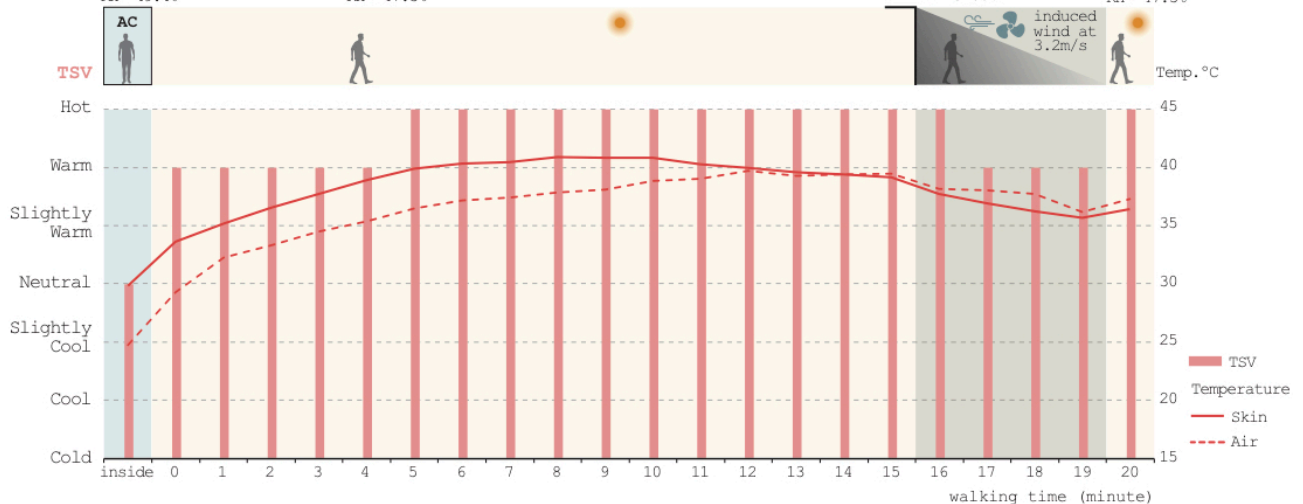


Figure 44 Graphs of the skin temperature, air temperature and TSV during the three climatic periods

5.4.6. Thermal comfort and thermal sensation

The thermal sensation and thermal comfort votes showed that the subjects were ‘comfortable’ and ‘just comfortable’ when they felt ‘slightly cool’, ‘neutral’ and ‘slightly warm’; this corresponds to the findings of (Dahlan and Gital, 2016). However, as they started to feel ‘warm’, some 60% changed their votes to ‘just uncomfortable’. Substantially, the subjects became ‘uncomfortable’ only when they felt ‘hot’ and never became ‘very uncomfortable’ even when they continued to walk for 20 minutes and endured the highest thermal sensation. Their justification was that they had expected their discomfort to get worse, although it never did. Accordingly, the psychological factor of ‘expectation’ played a role in improving their overall satisfaction. Therefore, in this study, the vote ‘warm’ has been considered the threshold for ‘comfort’ and has been used to identify tolerable walking times in the three climatic periods under review (Figure 45).

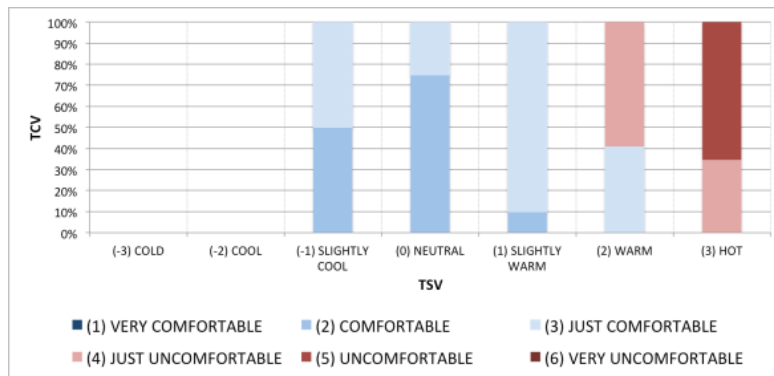


Figure 45 Bar chart showing the relation between the TSV and TCV

Looking at the TSV of the pedestrians immediately post transition and after being given 4 minutes in which to adapt it was recognized that when the subjects moved into shade, their post adaptation votes improved immediately after transition, from ‘warm’ immediately after transition to ‘slightly warm’ after 4 min, and from ‘warm’ immediately after transition to ‘neutral’ after 4 min. This applies to all subjects. Yet when the subjects moved to the sunny space, even when they had been given 4 minutes to adapt, this reduced their TSV alone, from ‘slightly warm’ immediately after transition to ‘warm’ after 4 min.

5.5. Conclusion

The study examined the influence of transitions within the thermal environment on pedestrians’ thermal sensations with a view to improving their comfort levels. The findings revealed that the influence of expectation played a major role in improving the comfort ranges for pedestrians, allowing them to walk longer even when feeling warm.

The tolerable walking time without shade has been found to be 8 minutes in the hot period of the year and 10 minutes in the warm and mild periods. Some factors have been shown to limit thermal comfort, such as widely different air temperature between indoors and outdoors, which influenced the thermal sensation and comfort levels negatively.

The influence of the transitions from air-conditioned space to non-shaded external space worsened the thermal sensation greatly, even in comparison to the transition from shaded to non-shaded after 19 minutes of walking. Therefore, promoting mechanically cooled spaces/units within the urban environment to promote walkability is highly critical for comfort. However, when passive interventions are insufficient to provide comfort, then to avoid discomfort the above principles of transition should be considered. Providing transitional conditions/spaces next to the exits from buildings would mediate such transitions. To improve its efficiency, the thermal conditions of this median space should be responsive to the changes in the outdoor conditions.

It may be noted that when the subjects had felt 'hot' for more than 5 minutes, a longer exposure to shade and wind was required before they once more felt comfortable. This depends on the air temperature and difference of wind speed between the two spaces. Therefore, the urban interventions intended for outdoor cooling should be designed linearly, giving pedestrians enough time to regain thermal neutrality. In Dubai, the high humidity levels, allow pedestrians to experience the sensation of moist skin, giving the wind greater potential to improve the thermal sensation. A wind speed of 3.2 m/s is deemed desirable for improving both TSV and TCV.

Changes in Tsk can be used to indicate the microclimatic conditions during the three climatic periods. A direct correlation between Ta and Tsk was found. Tsk is also indicative to the thermal transitions pedestrians endure within an urban continuum.

In this climate, it is not necessary in most months to provide full shading or cooling for outdoor spaces; short exposure to non-shaded areas was revealed to have no significant influence on thermal comfort. The findings correspond to the fact that the thermal sensation of pedestrians depends on the antecedent spaces in their walks. Shade and wind can be used only to extend the distance that pedestrians can travel if the routes are to be designed efficiently. The warm period has the highest potential for improving thermal comfort and thermal sensation by promoting solar control and wind movement. However, the influence of the transition from shade to sun seems to be unsatisfactory for both TSV and TCV. This requires further testing with multiple scenarios.

CHAPTER 6: Environmental Monitoring and Simulations

Acknowledgment of the urban climatology is one of the design features of outdoor spaces; the design is formulated in a microclimate that needs to be well understood and controlled, to create a better human environment. At the same time, understanding and being able to predict the microclimate may help us design these spaces to improve aspects of the performance of the adjacent buildings. If the environmental quality of the spaces is enhanced, it will further encourage people to stay outdoors. Variations in the configuration of the urban spaces can generate significant changes on the microclimatic parameters (e.g. temperature, relative humidity and wind speed). The microclimate depends upon the urban morphology, space orientation, materiality, anthropogenic heat sources, vegetation and other factors such as the state of the general and local climate. There is a shortage of information on the way the microclimate is influenced by such factors, which in turn affects the use of open spaces, along with subjective data for evaluating the comfort conditions in these outdoor spaces, which serve to help the design and planning of such spaces.

The urban density and geometry influence the solar penetration of the various materials that can store heat, as can the trapping of radiation by multiple reflections between the buildings and the street surface. Buildings or trees that hide the sky reduce the loss of long-wave radiative heat, which is intercepted by the obstructing surfaces, and absorbed or radiated back, whereas compact designs and means of solar protection such as trees and shading elements reduce this overheating in summer. However, such designs may also reduce airflow, promote multiple solar reflections and build up to evenings in which the heat is trapped (Kleerekoper et al., 2012).

In hot humid climates, where wind flow is much in demand for conditioning the climate outdoors, the geometry of the urban outdoor space should provide solar protection without impairing wind flow. This is very challenging to town planners, because creating more shade tends to block currents of air more efficiently, as most designers have unfortunately found. Therefore, it is important to test the different effects of shading strategies through fieldwork in any location, to determine which most effectively reduce temperatures in all seasons without impairing wind flow.

In this chapter, the climatic context of Dubai, multiple outdoor spaces have been studied in relation to the times of day that human activities take place, aiming to understand how the attributes of space influence the microclimatic conditions. In order to improve spatial design and provide outdoor cooling, the dominant environmental parameters (T_a , RH, T_g and V) require long-term monitoring. This chapter reviews the fieldwork and analysis conducted for an urban area to discover the influence of the physical attributes of the built environment on the microclimatic conditions. This was deemed to

provide an understanding to the ways urban spaces should be designed to improve the microclimate thus pedestrians comfort.

Furthermore, through the previous two chapters of fieldwork, thermal comfort and thermal sensation were investigated, to clarify the dynamic conditions to which pedestrians are exposed. It is suggested that shade and wind along the journey improved both TSV and TCV. Now we address the question of *how to improve or cool the microclimate or how to provide shade and wind?* Which forms of shade most effectively cool the microclimate and at what times of day and year are they most effective? Our purpose is to avoid creating uncomfortable spaces that lack wind flow and accumulate heat, such as some of the spaces where pedestrians in the fieldwork were stopped and interviewed. Therefore, it was essential to investigate the impact of the built environment in these locations.

6.1. The context

Several spaces in the Jumeirah Lakes Towers district were selected for environmental monitoring, (see section 4.1.1.). These spaces lie along the route taken by the most pedestrians, a route which links the metro station to the office buildings. Each of the spaces provide a range of conditions typical to most communities in Dubai, from vegetated or bare to shaded (by buildings or by built canopies).

The urban district contains an artificial lake, which is a very common attraction in many locations around the city. However, each of the spaces selected has its own form of solar protection and wind permeability; they resemble one another in material but are different in form. The main feature is that the heat balance between diurnal gains and nocturnal losses in each space is individual, due to the influence of its geometry on its microclimate.

6.2. Data logging procedure

6.2.1. Aim

This aim in using this method was to assess the influence of the space morphology on the microclimatic parameters. Different sources of shade were investigated, such as that provided from a canopy, trees, buildings and non-shaded spaces. Understanding the effectiveness of these different sources at different times of the day and year helped to identify the most efficient at a particular time of the day and climatic period. It also helped to understand the behaviour of the space typologies.

The goal was to identify the most effective way of cooling the spaces, i.e. of reducing both the air temperature and the mean radiant temperature and increasing the wind flow. These proved through

the fieldwork presented in Chapters 4 and 5, to be most effective to improve pedestrians thermal comfort. The high humidity levels could then be tolerated, as discussed previously.

6.2.2. Space typologies

Data loggers were installed in four different spaces in the JLT district, Spaces A, B, C and D (Figure 46). Each space provides a different form of solar protection and wind permeability. However, all spaces exhibit similar materials in various ratios. The ground was covered mainly in light grey concrete tiles and some pathways were covered with beige interlocking tiles. Patches of greenery were scattered throughout the route, although none of the selected spaces had a large enough area of grass to influence the assessment. A more detailed description of each space is presented below.

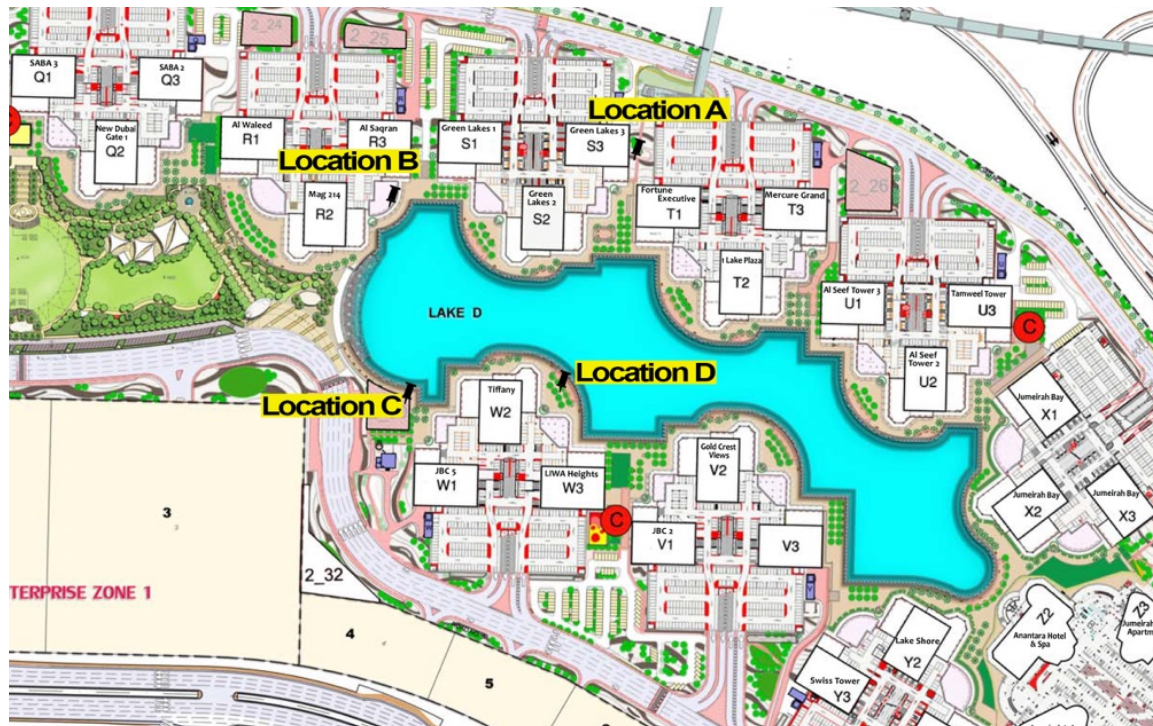


Figure 46 Map of JLT indicating the location of the four spaces used for environmental measurements

Space A adjoins to the metro station, which has an adjacent building that provides shade. The space has a paved pathway between two poorly vegetated sand patches (Figure 47). During most of the day, all year, the building provides shade along the path except during noontime. The paths of the space offer no shade in the form of trees.



Figure 47 Image of Space A (right) and diagram (left) showing the space geometry

Space B is a space that is often shaded except during the early mornings during the mild period. The space consists of a concrete arcade that overlooks the artificial lake (Figure 48). The arcades are a typical feature in many of the spaces within the area. At the corner of the space, lies an opening that leads to the car park, which people use as a short cut instead of walking along the lake.



Figure 48 Image of Space B (right) and diagram (left) showing the space geometry

Space C is a linear pathway along a lake, which is aesthetically pleasant to walk through and aesthetically pleasant (Figure 49). It is, however, a bare strip shaded neither by buildings nor by trees, that connects an office building with a metro station and many other facilities within the district serving all the local pedestrians.



Figure 49 Image of Space C (right) and diagram (left) showing the space geometry

Space D is a pathway covered by deciduous trees and shrubs that often provide unbroken shade (Figure 50). The decision to use deciduous trees in this region was very surprising, even where continuous shade is prized. However, the solar penetration in the season when the trees were bare helped to analyse the varying influence of the humidity levels.

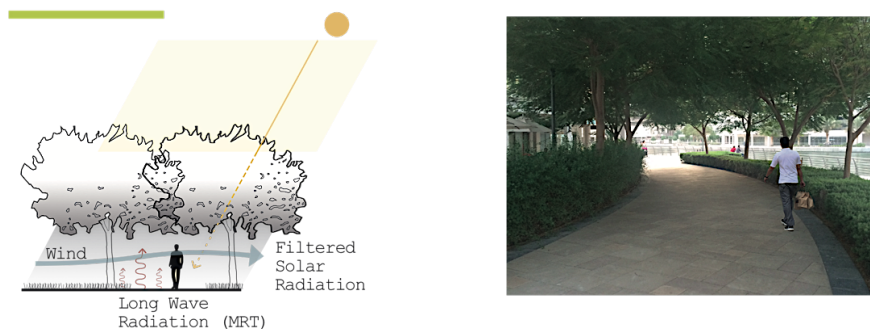


Figure 50 Image of Space D (right) and diagram (left) showing the space geometry

6.2.3. Instrumentation

A measuring station was created and moved between the four spaces in turn. The station consisted of two loggers mounted into a wooden perforated box 15 X 15 X 30cm (Figure 51). The box was then attached to a wooden stand 1.7m high, corresponding to the average height of the centre of gravity for adults and a base 60 X 60cm. This station was used for the measurements in all the spaces.

Ta, RH and Tg were measured, consecutively in each space, for 5 days each month (totalling 20 days each month). Spaces were measured during a single year between April 2015 and March 2016, inclusive.

The first logger was a TGP-4500 'Tiny Tag' data logger, which was used to measure the humidity and air temperature (Appendix B). The globe temperature was measured through the other logger, TGP-4505 'Tiny Tag' hand-held data logger with a thermistor probe. A 40mm hollow acrylic sphere coated in matt grey paint (RAL 7001), 38 mm in diameter and 1 mm thick, with a Pt100 sensor at its centre was attached to the thermometer.



Figure 51 Image of the wooden station created for the long-term measurements showing the ventilated box with loggers inside. White plastic bags of sand were used to stabilize the base.

This was a model which had been used in several outdoor studies (e.g. (Yahia and Johansson, 2013; S. Thorsson et al., 2007). Both the ISO 7730 (ISO 7730, 2005) and the ASHRAE Handbook of Fundamentals (Brager and de Dear, 2001) suggest a medium grey colour instead of black when the globe is exposed to solar radiation, to align better with the outer surface of people's clothes (Johansson et al., 2014). The matt grey colour slightly exaggerates the T_{mrt} in shady conditions and slightly underestimates it in non-shady conditions. Previous studies have shown that a standard black globe overstates the influence of short-wave radiation whereas a matt grey globe better represents the radiation characteristics of normal clothing (Olesen et al., 1989).

6.2.4. Data analysis

In each space, for five consecutive days each month, the measurements every two minutes were recorded by the loggers. The data of the five days were averaged to one representative day for each month. The months were then averaged into climatic periods of mild (December, January, February and March); warm (April and November); and hot (May, June, July, August, September and October). This classification is consistent with the fieldwork conducted previously. The focus fell on three times of day – 8:00, 12:30 and 17:00 – when the spaces were occupied by pedestrians on their way to work, during their lunch break and back from work.

6.3. Outcomes from data loggers

The graphs of the daily T_a , RH and T_g for the three periods is presented below from Figure 52 to Figure 60. A table placed beneath each graph shows the space name and the recorded value, arranged from highest to lowest. This table is set to ease the readability of the values in the above graph revealing the optimum space in each condition. The left margin of the table illustrates the T_a difference, T_g difference and RH difference between the coolest and warmest space to reveal the effectiveness of the coolest space configuration in improving the microclimatic parameter discussed in that figure. This information also determines the diurnal variations between one space and another during each period.

6.3.1. The mild period

In the mild period, space A, the most pleasant for pedestrians, was the warmest space in the mornings, followed by spaces C, D and B, in that order (Figure 52). Full shade was provided along the path in space A owing to the angle of the sun. However, at midday, space D, was the warmest space followed by spaces A, C, and B, in that order. There was a significant difference of 5.4°C in Ta between spaces D and B. The reason was that space D, due to the low angle of the sun at this time of year, was not shaded. The solar radiation that had accumulated since the morning had been blocked by trees. This rise in Ta continued until the afternoon, allowing space D to be the warmest followed by spaces A, C and B in that order. The diurnal differences between the four spaces were greatest at midday. This is due to the maximized effectiveness of shade on reducing the air temperature.

Space B was consistently the coolest space during the mild period at the three chosen times of day. This was predictable from the continuous shade provided in the space all day. It was also observed that space A, which lacked any form of solar protection, was equally not the warmest space at any time of day. In the previous interviews, this space had been found to have the highest ventilation and wind speed values.

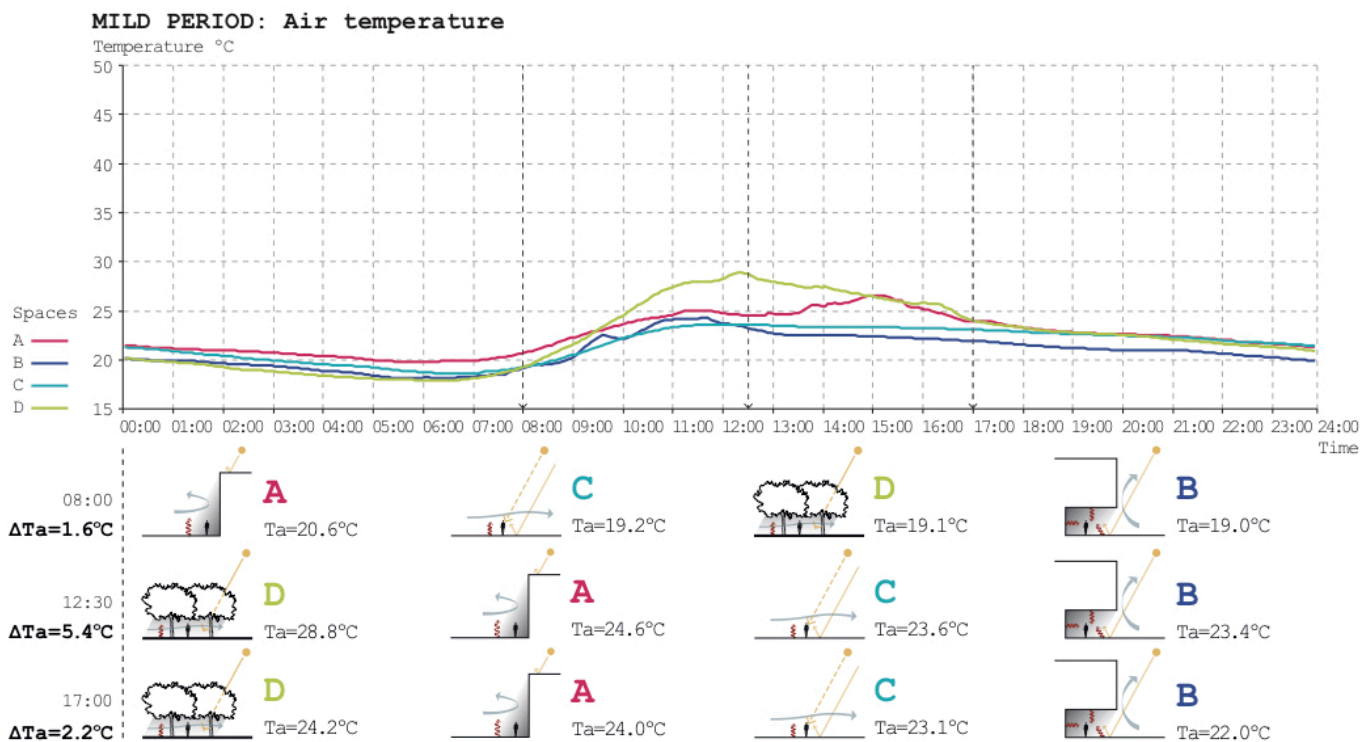


Figure 52 Graph showing the measured air temperature values of the four spaces A, B, C, and D all day during the mild period

In general the global radiation values recorded were very similar to those for air temperature. However, the global temperature pattern was slightly similar but not quite the same as the air temperature values. Still, the highest values of the spaces were the same. At 8:00, space A recorded the highest values, while space D did so at 12:30 and at 17:00 (Figure 53). However at midday, unexpectedly, space D was cooler by 10⁰C than space C, which is a significant difference. This highlights the influence on the temperature values of blocking the heat and space ventilation. Such values also shed light on the extent to which an inappropriate design input can harm the microclimatic conditions instead of improving them. Space C recorded the lowest values for both morning and midday readings, which indicates that the radiation levels before noon should not be a concern for urban designers. This finding also corresponds with previous findings from the fieldwork (interviews and experiments) that the lack of shade did not cause discomfort; conditions were reported in most cases to be satisfactory.

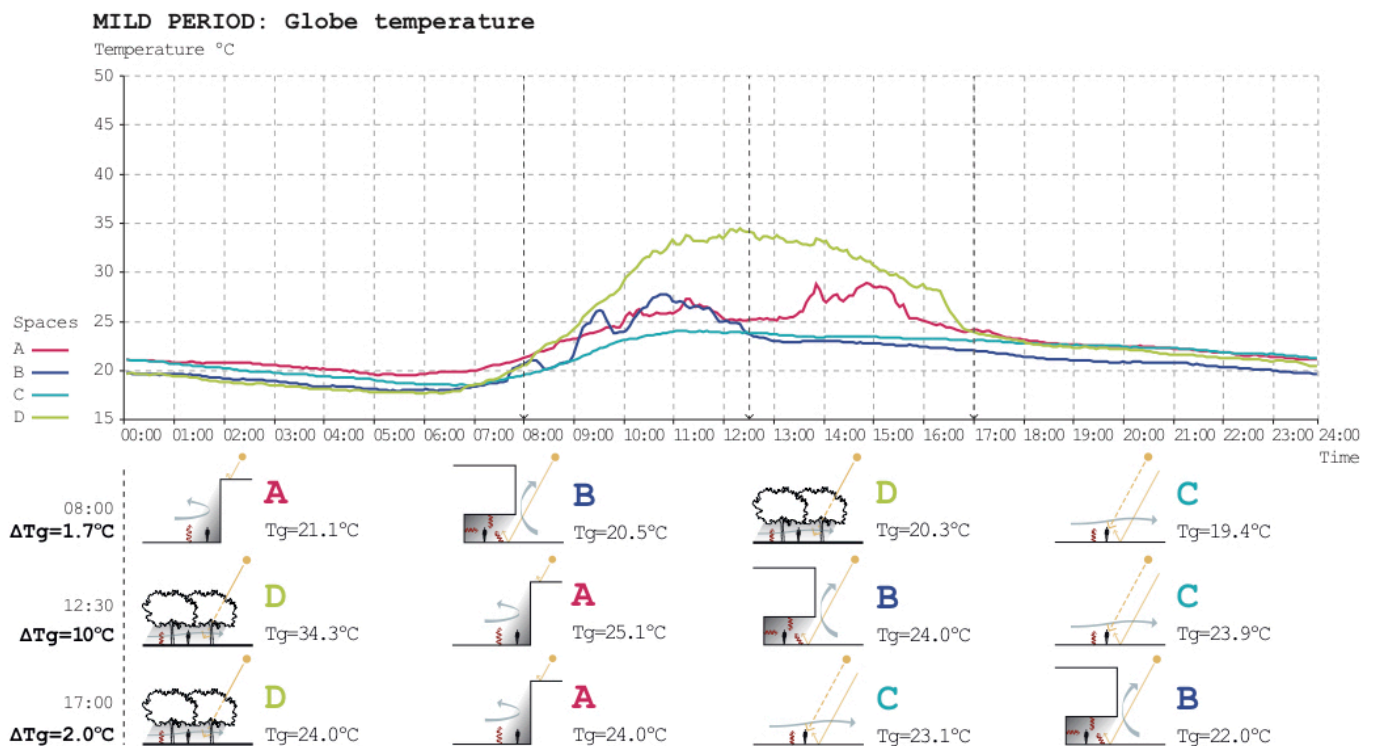


Figure 53 Graph showing the measured globe temperature values of the four spaces A, B, C, and D all day during the mild period

Space D here had the highest value in the morning, yet the lowest at midday and in the afternoon, while space C registered as the most humid at the two latter times of day (Figure 54). This was deemed to be logical in relation to the air temperature values. The differences between the highest and lowest values were maximized again at midday, comparable to what was reported for Ta and Tg. Space B was consistently the second least humid space all day long.

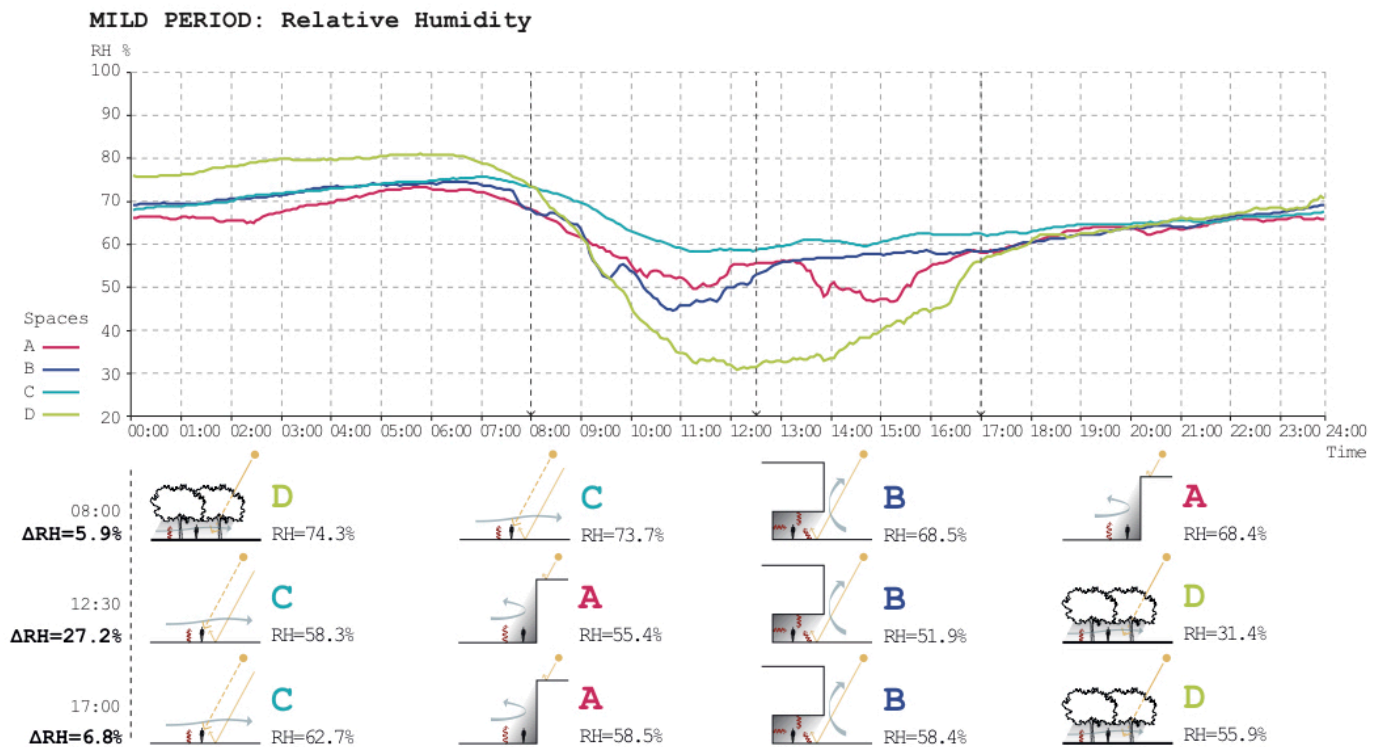


Figure 54 Graph showing the measured relative humidity values of the four spaces A, B, C, and D all day during the mild period

6.3.2. The warm period

During the warm period, there were relatively slight differences in T_a between the four spaces and the differences between their highest and lowest values were still the highest at midday (Figure 55). Space C was the warmest space throughout the day, due to its lack of solar protection. The second warmest space throughout the day was space D also, which had been expected to offer a better performance. Space A was the coolest in the morning and afternoon so long as shade was provided. At midday with the sun directly above, space B was the coolest. The behaviour of the four spaces in this period was very dependent upon the presence of shade.

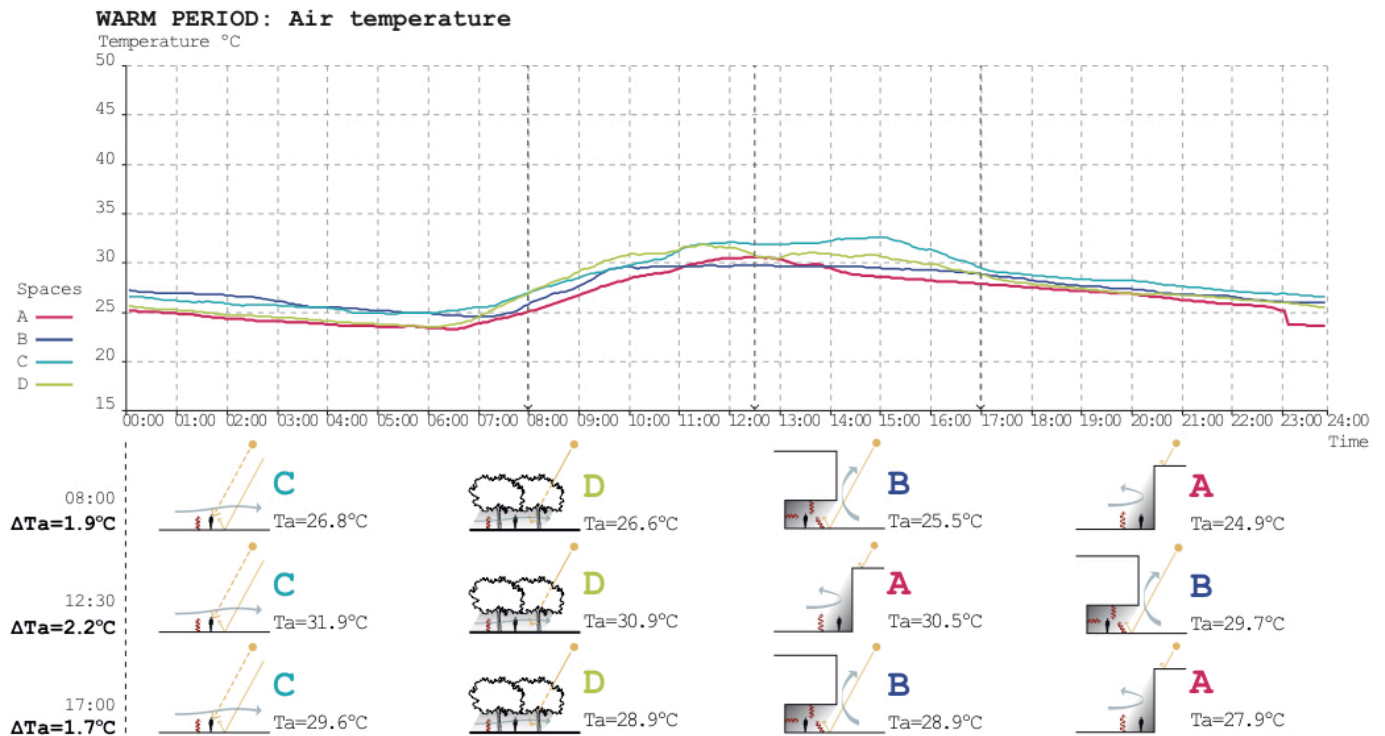


Figure 55 Graph showing the measured air temperature values of the four spaces A, B, C, and D all day during the warm period

The order of the spaces regarding the level of their performance) in Tg was similar to that in Ta. However, the values recorded (the differences between maximum and minimum) showed a wide span (Figure 56). Space D recorded the highest values in the morning while space C remained the highest at midday and in the afternoon. Spaces A and B recorded the lowest and second lowest values at the three times of day. The values for space A as the coolest space in the warm months is similar to those recorded for Ta in the mild period. Differences between the highest and lowest values were greatest again at midday reaching almost 7°C.

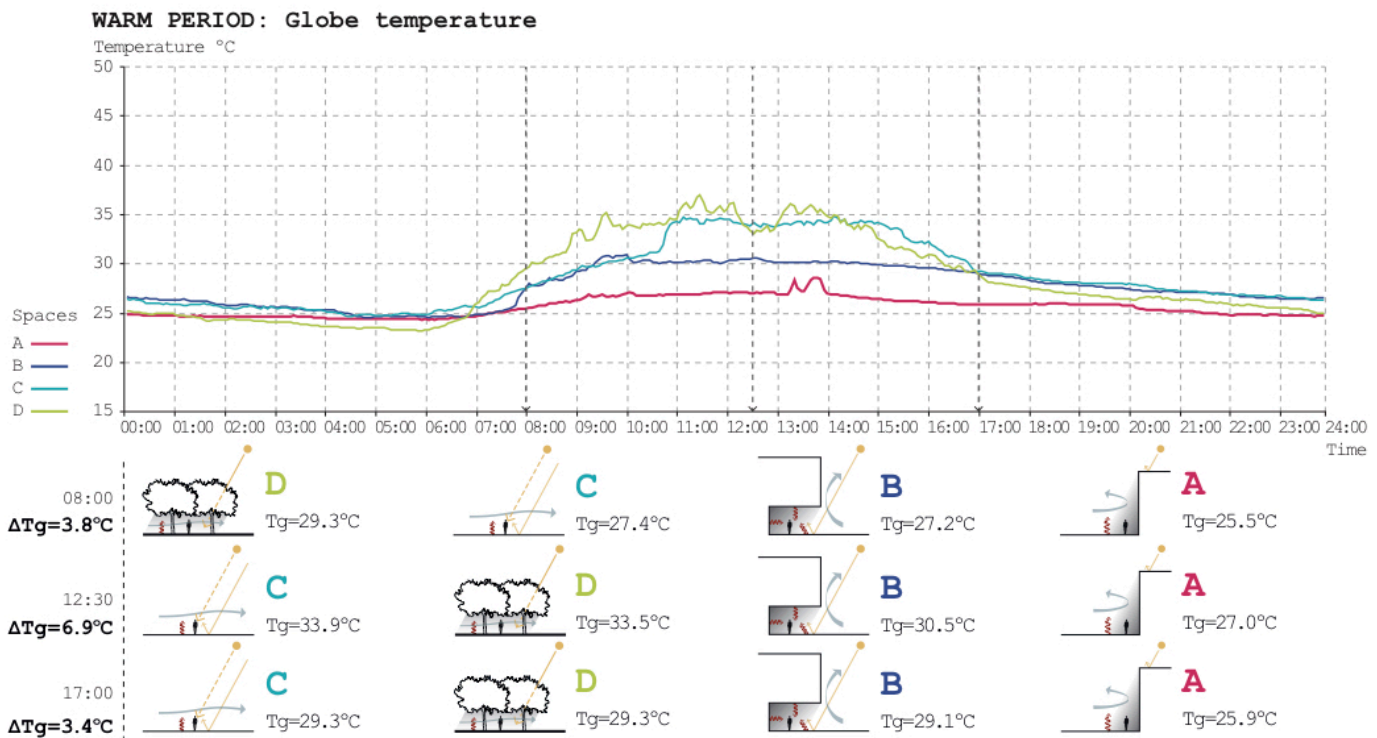


Figure 56 Graph showing the measured globe temperature values of the four spaces A, B, C, and D all day during the warm period

Space B was found to be the most humid space throughout the day, followed by spaces A, C, and D (Figure 57). Space B lacked ventilation at all times, trapping the heat there. This behaviour was more marked as the weather got warmer. The record of relative humidity was consistent throughout the day for all spaces with significant differences between maximum and minimum values.

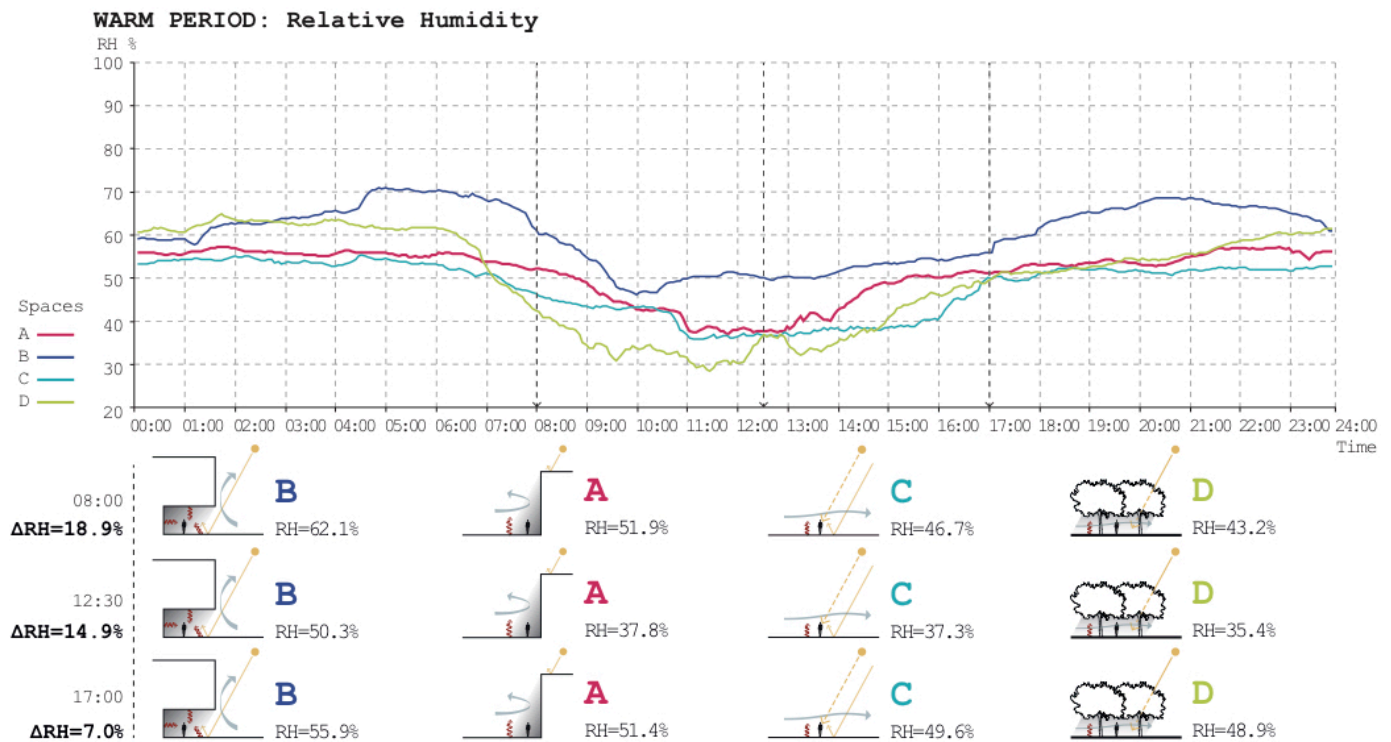


Figure 57 Graph showing the measured relative humidity values of the four spaces A, B, C, and D all day during the warm period

6.3.2. The hot period

It is worth noting that the differences between the four spaces were the lowest in this period, the greatest difference between maximum and minimum values appearing at midday (Figure 58). The levels in space D were highest at midday and in the afternoon, while space C was the warmest of the four in the morning. Space A was the coolest space throughout the day. The reason was that the morphology of space A always provided shade without any horizontal obstruction to block ventilation or heat release. This behaviour was similar for this space throughout the three periods. Space B, with full shade, recorded the second lowest values at midday and in the afternoon and space D did so in the morning. This highlights the importance of shade at this season to reduce the air temperature in the spaces.

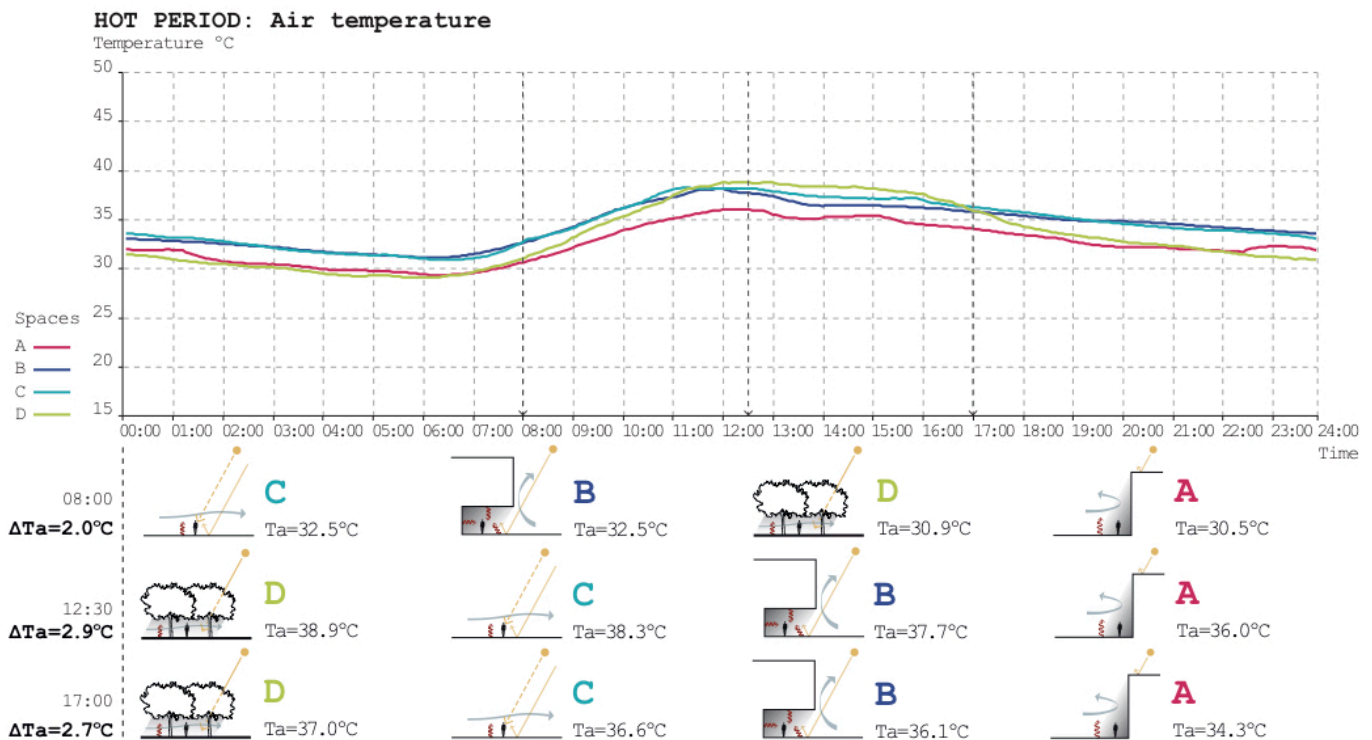


Figure 58 Graph showing the measured air temperature values of the four spaces A, B, C, and D all day during the hot period

Interestingly, all spaces held the same pattern of readings for both the Ta and Tg. Space A recorded the lowest global temperatures throughout the day (Figure 59). This means that in the hot period space A was the best at reducing both the air and global temperatures. It is noteworthy that space A reduced the air temperature at noon by 11.7°C more than space D did, though both spaces were shaded. The cause of this was inferred to be the lack of ventilation and entrapment of heat. The order of spaces in terms of coolest highlights the importance of shade in reducing the radiations into the spaces at this time of year; however, trees do not conduce to this effect. Other spaces should however be studied before confirming this judgement; the point is investigated further in the microclimatic simulations that are presented in the following section.

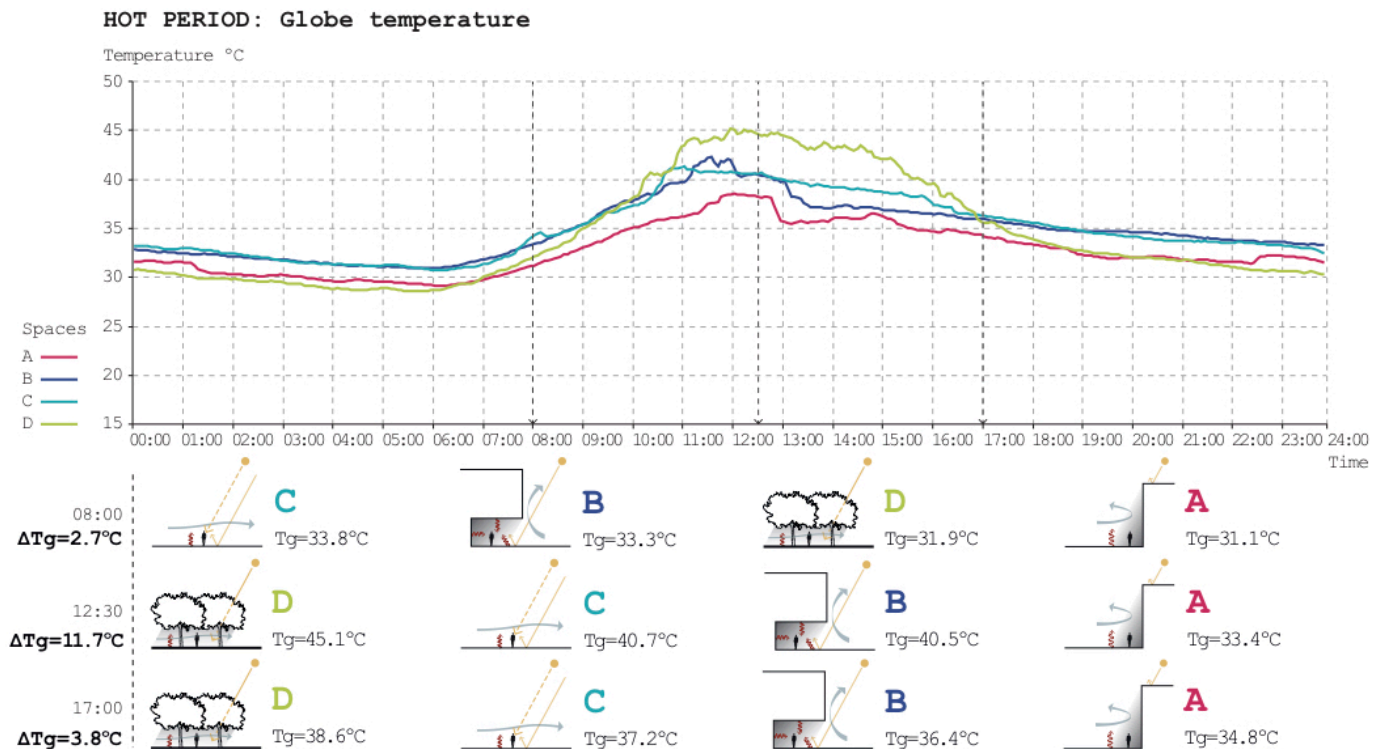


Figure 59 Graph showing the measured globe temperature values of the four spaces A, B, C, and D all day during the hot period

Space B recorded the highest humidity levels throughout the day, while space C recorded the lowest (Figure 60). The differences between the values throughout the day were the lowest in this season, yet the moisture content of the air is the highest of the year. This microclimatic parameter was reported by many pedestrians as the reason for their discomfort.

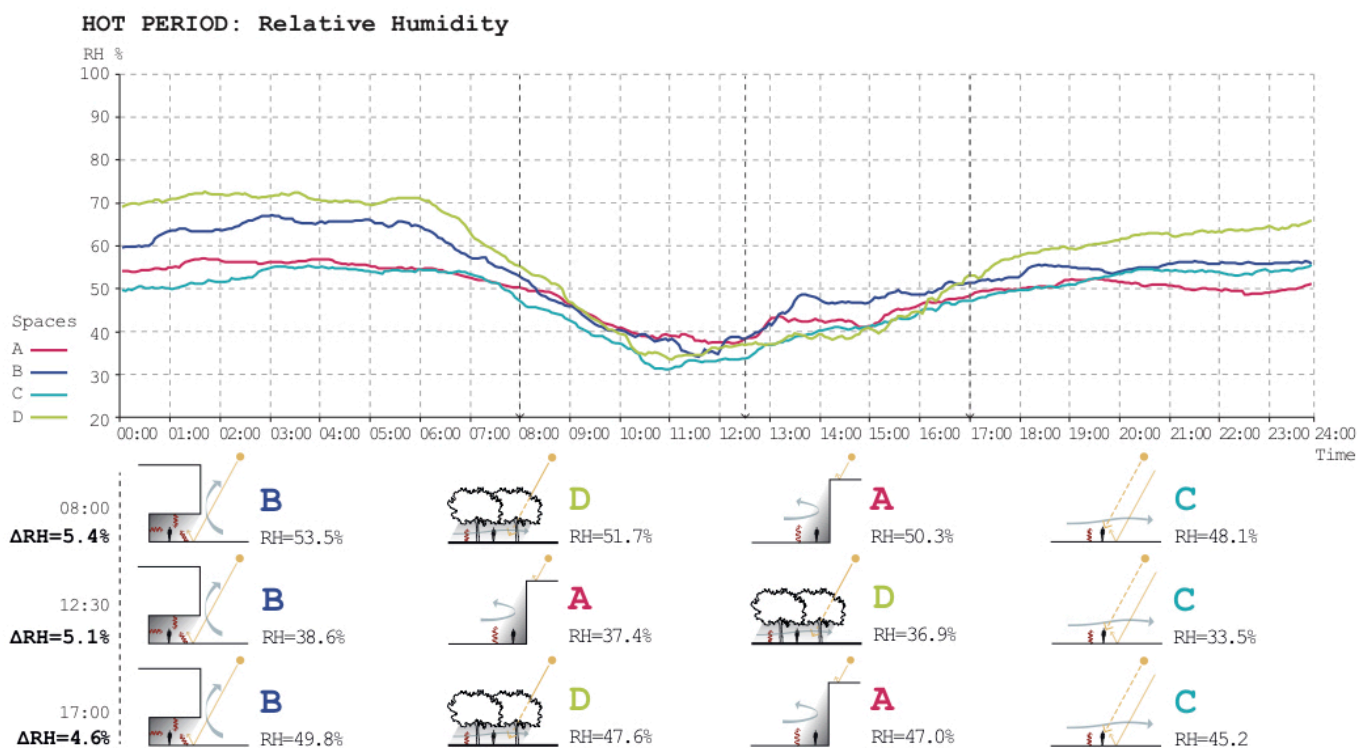


Figure 60 Graph showing the measured relative humidity values of the four spaces A, B, C, and D all day during the hot period

6.4. Conclusion

It can be concluded that the spaces that provided higher levels of solar protection lost less heat in the evening and were thus warmer at night. Space D, with its trees and shrubs did not provide pleasant conditions, whereas space A, in the shade of a building, which was properly ventilated and had no horizontal shading device to obstruct the release of heat was generally the coolest space at most times of the day and most months.

The balance required between solar protection and wind flow depends on the period. Though none of the factors can be completely ignored, wind may be regarded as more important in the mild period. In the morning and afternoon in the warm period. These are times when the solar radiation is lower than it is at other times of year. During the hot period and at midday in the warm period, shade should be prioritized, so long as air currents are unimpeded. At the chosen times of day, the wind flow alone cannot lower the temperature due to the high temperature of wind and the high radiations.

The influence of the built environment on the microclimatic conditions was significant. Differences between the air and globe temperatures of the various spaces reached 11°C. This means that spaces should essentially be designed to cool the air within them based on actual performance studies in the climate where the design will be applied.

Even fully shaded spaces cannot be considered optimum all year without the presence of wind flow. Spaces that obstruct heat radiation flushing can turn out to be warmer than non-shaded ones.

In general, no single space was found to perform optimally at all three times of day in all the different climatic periods. Therefore, spaces should be designed according to the times when they are most used. Space D, which was mostly cooler in the evenings was hardly ever occupied then.

Wind measurements were not included in the data logging process, due to the limitations of the tools and the need for approval from the authorities. However, since it is important to understand the influence of space ventilation on heat performance, this gap was investigated randomly through spot measurements in each space whenever interviews were being held.

6.5. Microclimatic simulation

6.5.1. Aim

Microclimatic simulations are a very useful tool when investigating the microclimate at many scales due to the interweaving of the multiple parameters present in an outdoor environment, which makes

it very complex to control. These softwares gives the researchers a chance to analyse outdoor spaces on a much wider scale, to help them understand some behavioural patterns, which could not be justified when fieldwork is conducted.

However, fieldwork remains most validated methods to measure and investigate microclimates. When both tools are combined, much deeper knowledge could be achieved. At this stage, a microclimatic simulation tool named ENVI-met was used to understand the influence of the morphological characteristics on the microclimatic parameters of various outdoor spaces that has been investigated through environmental monitoring.

Moreover, the microclimatic conditions are to be overlooked from a larger scale rather than a street level as conducted during fieldwork. The behaviour of the environmental parameters within these spaces needs to be analysed holistically in relation to the surrounding spaces, which field measurements does not allow.

ENVI-met was also used to identify hot spots and windless locations within the urban district and see whether they influenced the readings of the data logging. Besides, the direction, pattern, and intensity of wind was analysed carefully through this simulation tool to compensate the lack of wind speed measurements during fieldwork. The purpose of the images and graphs extracted from the simulations run are to analyse the influence of the massing blocks of an urban area on the wind and solar access through the site and how it influences the parameters within the spaces measured to help predict a solution to improve thermal comfort.

6.5.2. ENVI-met

ENVI-met is three-dimensional microclimatic simulation software dedicated for outdoor investigations (Bruse 2004). There are several reasons that made such tool selected for the analytical process. It focuses upon all the dimensions of the environment such as the atmosphere, the soil and all the surfaces in a space. The software incorporates all the imperative parameters valid in an outdoor environment which attains validated results. The software is designed to simulate the surface–plant–air interactions in urban environment. The ground surface, vegetation, buildings surfaces and elements within the space are all incorporated in the calculations of the heat sources of an outdoor space. It also has the advantage of incorporating different types of vegetation deeming the foliage temperature, the heat and vapour exchange within the air canopy which is one of the crucial variables of the study.

Considering the wind effect in the statistical analysis of the results is essential and provided by such tool where the wind flow field is treated as a normal prognostic variable and calculated each step. Moreover, the software is designed for micro-scale with a typical horizontal resolution from 0.5 to 10 m and a typical time frame of 24 to 48 hours with a time step of 10 secs at maximum. This resolution allows analysing small-scale interactions between individual buildings, surfaces and plants that is appropriate for this research (Bruse and Fleer, 1998).

The latest version of ENVI-met made it viable to simulate building canopies and arcades. Previous studies have analysed outdoor thermal environments by taking various measurements and then performing simulations based on the ENVI-met 4.0 model. The ENVI-met model is normally utilized to simulate urban and landscaped environments in terms of potential temperature, mean radiant temperature, wind speed, wind direction, and other variables. It has been adopted to conduct research in countries in multiple climate zones, which helps comparing the thermal performances before and after a particular configuration or design is implemented.

6.5.3. Simulation initialization

The geographic position of Dubai was given as Latitude: 25.25° and longitude: 55.33°. Three simulations were run resembling the three climatic periods, during 21st January 21st April and 21st September between 6:00-18:00 of 12 hours.

The urban area of JLT was selected focusing on the journey identified previously during the environmental monitoring Figure 61 and Figure 62. The four spaces are included along within the boundary for the area simulated. This area also included one of the journeys that were analysed, where pedestrians were interviewed.

The software grid resolution was 2mx2mx2m for the X, Y and Z respectively. This means that each grid cell in the drawing space represents two meters. This was found to be sufficient to provide accurate results at this climatic.

The model was rotated to allow minimum skewed lines. Buildings were considered flat with no projections yet, all arcades at the ground level were simulated.

The height of the arcade was modelled as 3m. Building roofs were flat. Three grid units were set along the X, Y and Z axis giving a total of 6m. This allows wind to penetrate the edges of the simulated area more accurately.

A telescoping factor 5% was set to allow the exact building heights to be modelled. All buildings were set at 160 meters assuming an average of 38 floors.

The modelled vegetation was very copied from the existing site conditions such as grass, palm trees and 10m wide canopy trees. The central lake was added given a depth of 5m.

The inside temperature of the buildings was given by default by the software as 200C, which is similar to that set in most indoor spaces. A 150x150x30 grid resolution was used to run the simulations. the saving intervals for the output files was set at each 60 min.

The initial temperature and the relative humidity values were the only parameter changed between the three climatic periods.

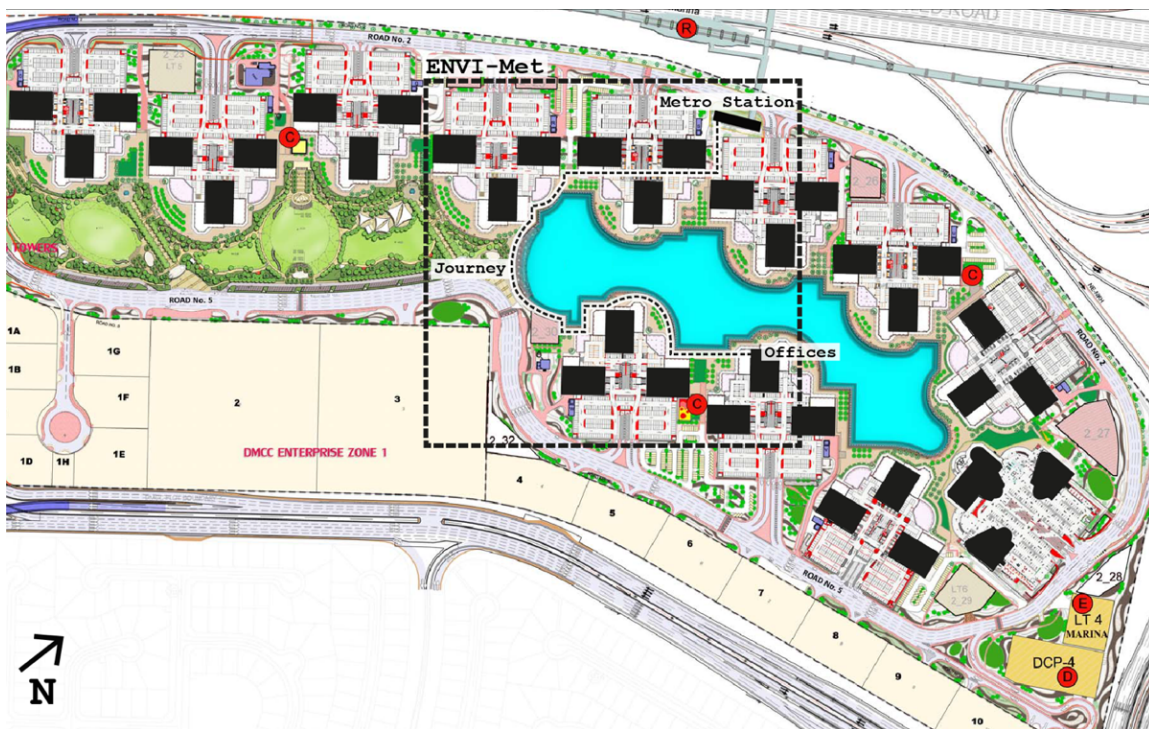


Figure 61 JLT map highlighting the modelled area

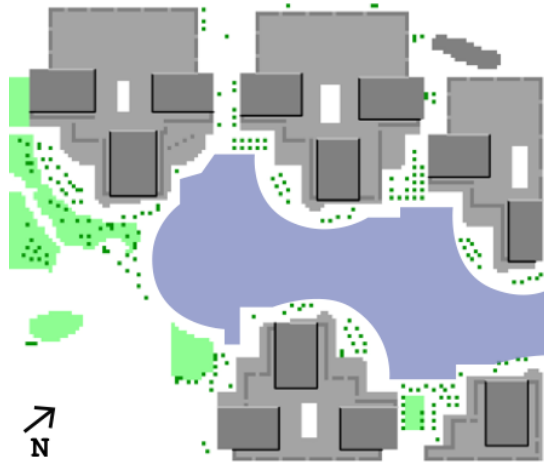


Figure 62 The modelled area on ENVI-met (buildings, lake and landscape)

6.5.4. Data extraction

Visual maps extracted from the output files of all the simulations by LOENARDO software were done for every 60 minutes for each month. Comparisons was also extracted between April and January and between September and January were January represents the base case or the pleasant conditions.

The maps provided visual coloured representations of the air temperature gradient, wind speed, mean radiant temperature and PET. Each map had its own colour coded key as set by the software, which should not be compared visually due to the different representation of values for each colour. Therefore, it is important to refer to the original values of the grid cells in each map independently and not comparing maps based on colours. This has been considered one of the main software limitations before 2014, when the new version was released ENVI-met 4.0.

The software capabilities have expanded vastly in terms of modelling, data extraction and analysis. The latest version of the software, ENVI-met 4.2, has been used during this study. Absolutes and comparative analysis were done between the visuals extracted and interpretations of the T_a , MRT, V and PET were done simultaneously. Focus has been given to the trip from the metro office building to the metro station which has been consistently investigated through fieldwork (interviews and environmental monitoring), therefore maps were extracted at 8:30, 12:30 and 16:30. Each map represents a specific timing and day.

6.6. Outcomes from ENVI-met

6.6.1. The mild period (January)

During the morning time the air temperature ranged between 26.9^o and 27.8^oC, 32^o and 34.1^oC during midday (Figure 63) and between 33.5^o and 34.8^o during the late afternoon (Figure 64 and Figure 65). The average temperature throughout the day was 30.9^oC. The maximum temperature value was recorded during the afternoon 34.8^oC and the minimum value during the morning was 26.9^oC.

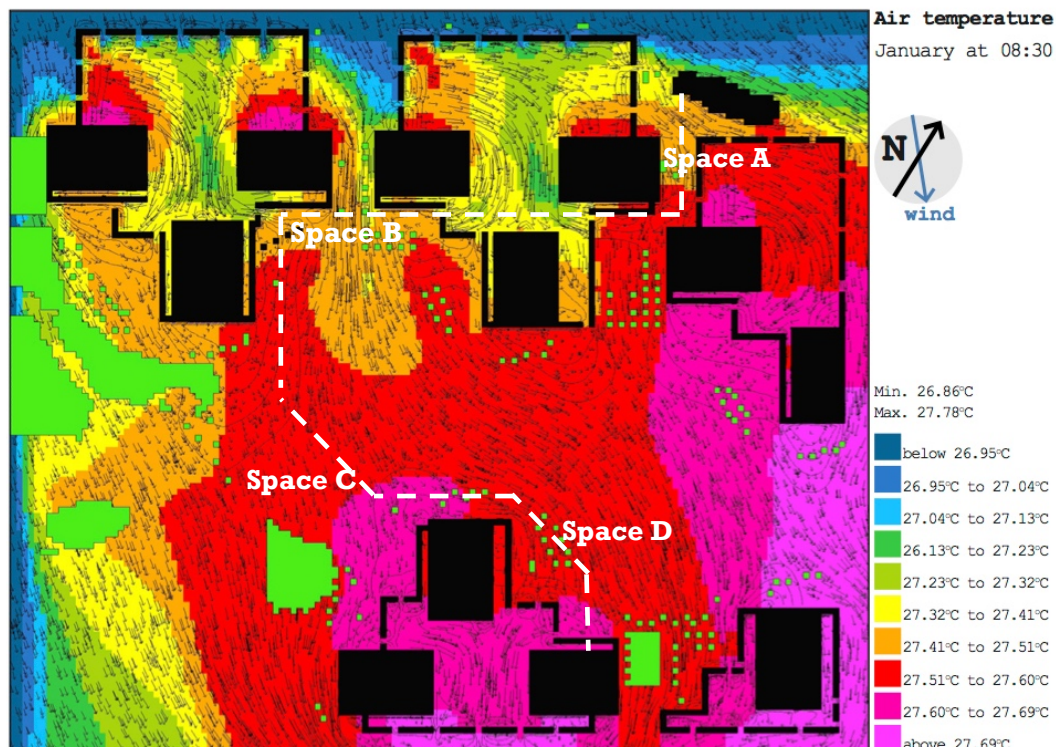


Figure 63 Air temperature, January at 8:30

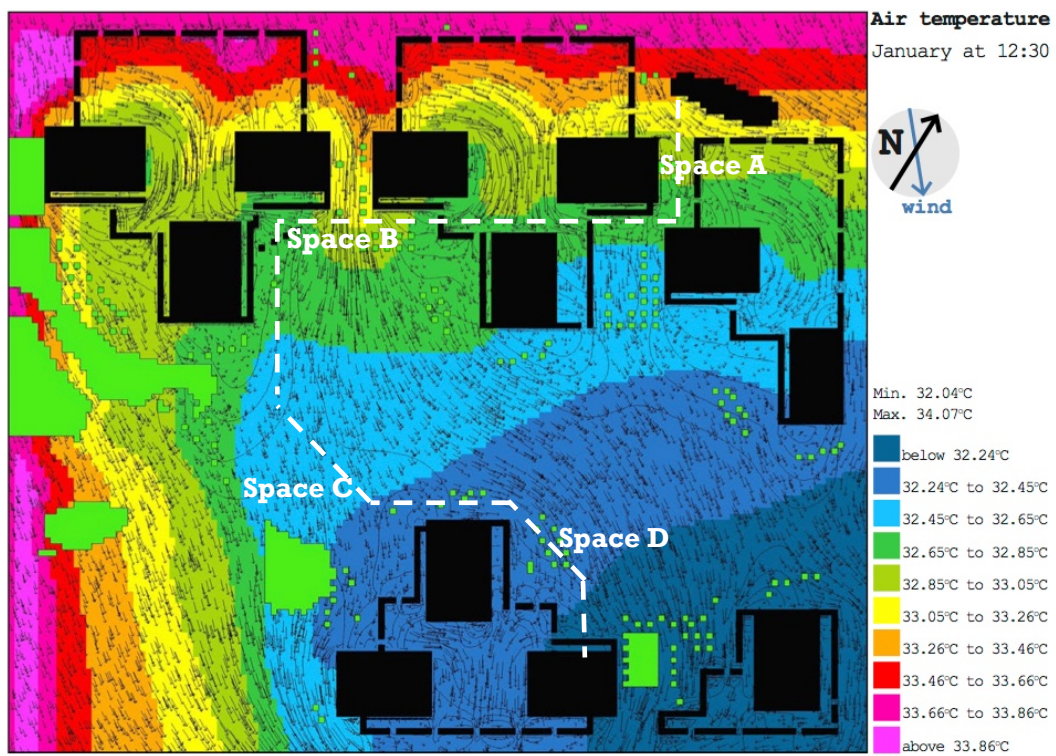


Figure 64 Air temperature, January at 12:30

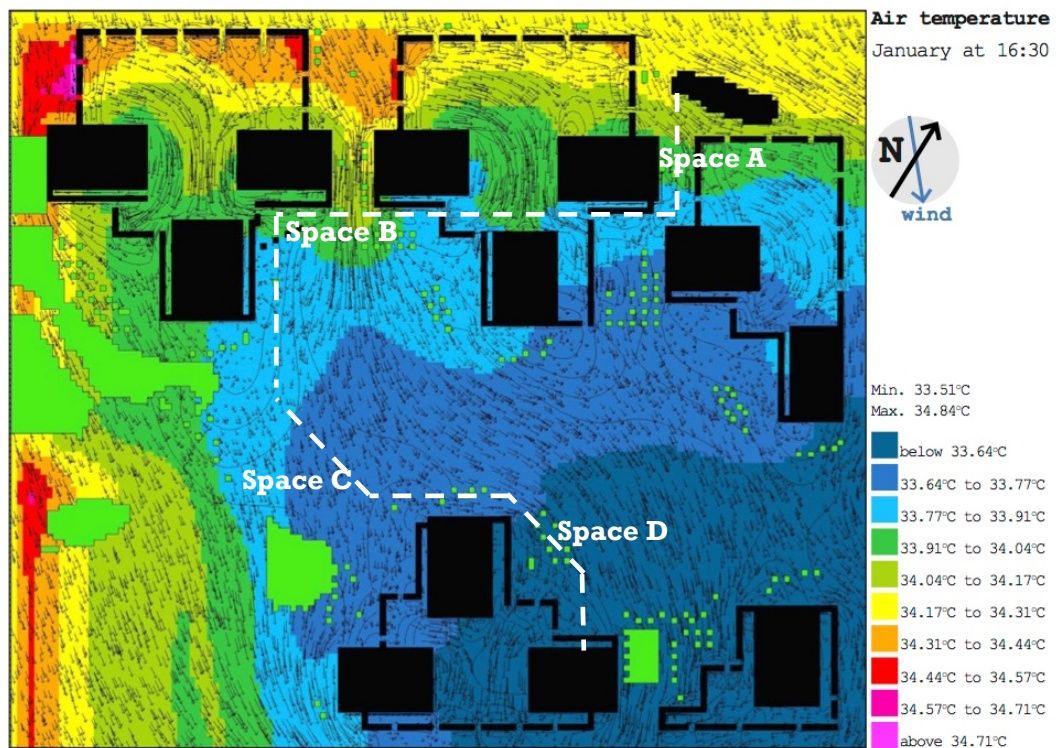


Figure 65 Air temperature, January at 16:30

The mean radiant temperature is clearly defined by the shade of the building blocks. A limitation was found within the capabilities of the software in the visual representation of the shadow casted inside the parking garages. However, this was only shown when the MRT maps were extracted and not the air temperature values.

During the morning time the MRT ranged between 21.7° and 46.1°C (Figure 66), 40° and 67.9°C during midday (Figure 67) and between 32.5° and 54.8° during the late afternoon (Figure 68). The average MRT throughout the day was 44.8°C. The maximum value was recorded during midday reaching 67.9°C which is due to the highest solar radiation levels. The minimum value was recorded during the morning 21.7°C.

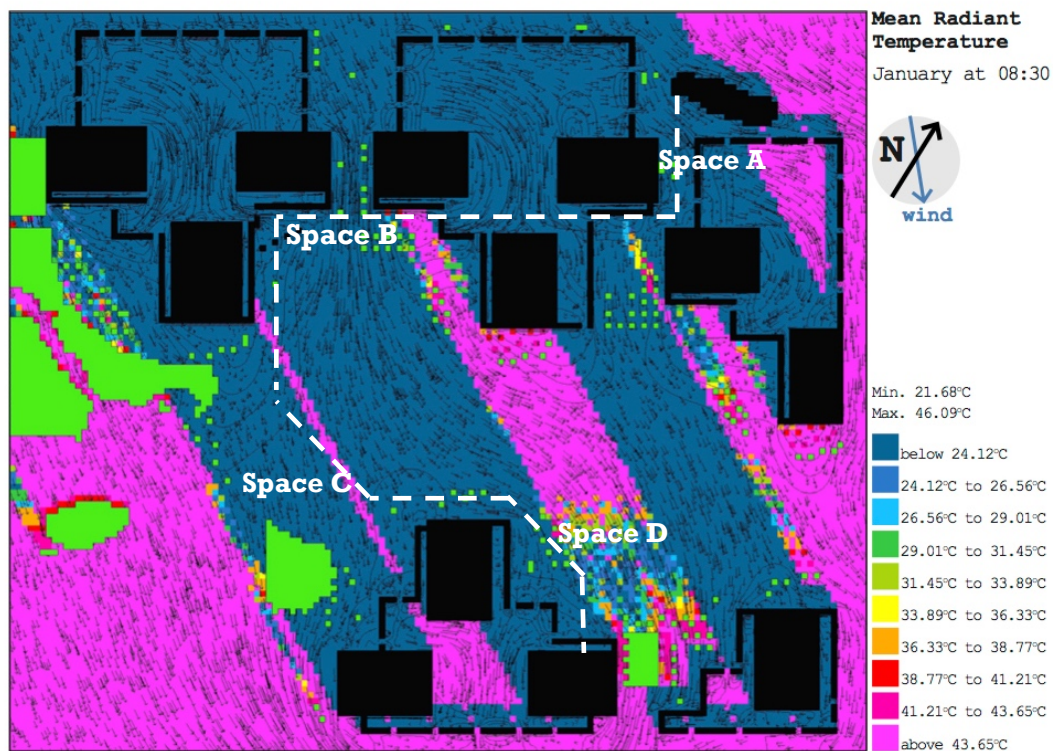


Figure 66 MRT, January at 8:30

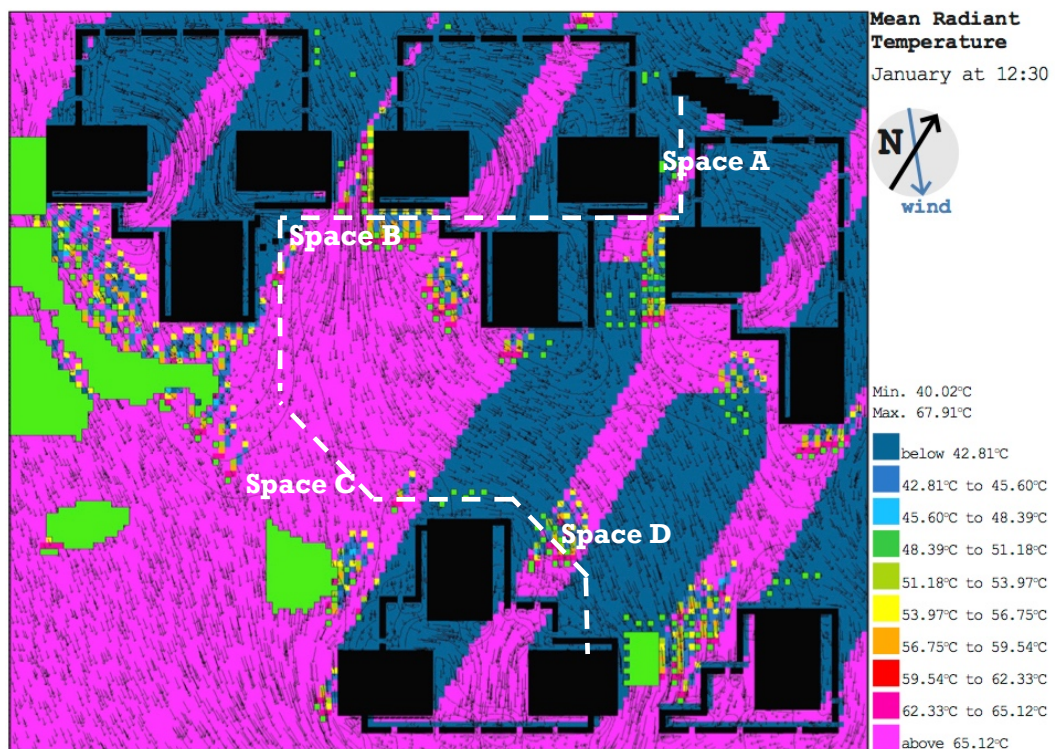


Figure 67 MRT, January at 12:30

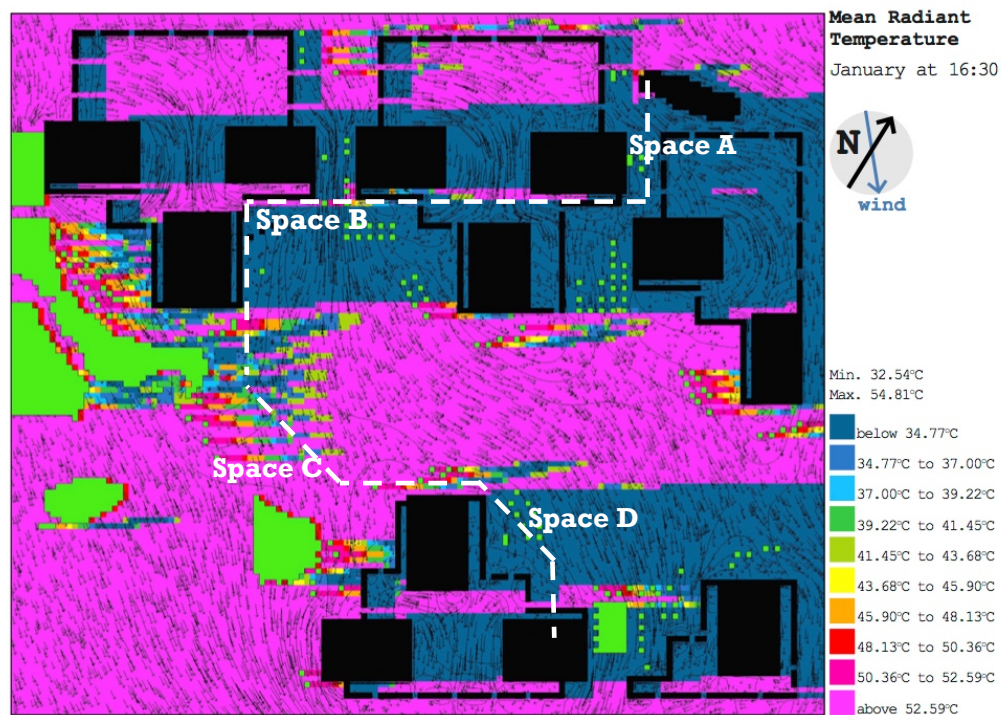


Figure 68 MRT, January at 16:30

During the morning time the wind speed values ranged between 0 and 6.1m/s (Figure 69), 0 and 5.9m/s during midday (Figure 70) and between 0 and 5.7m/s during the late afternoon (Figure 71). The maximum values of wind ranged between 5.7 and 6.1m/s were recorded between the two buildings parallel to the wind direction. Such composition caused a tunnelling effect which was consistent throughout the day and influenced a large area of the site. Areas where there was a staggered layout of buildings reduced the wind speed dramatically. Inside the parking garages a turbulence effect was caused due to the orientation and location of openings. When correlating such finding with the rise of air temperature revealed, it explained the reason why those spaces were warmer and at sometimes when compared to other non-shaded open spaces, which was noticed during the fieldwork.

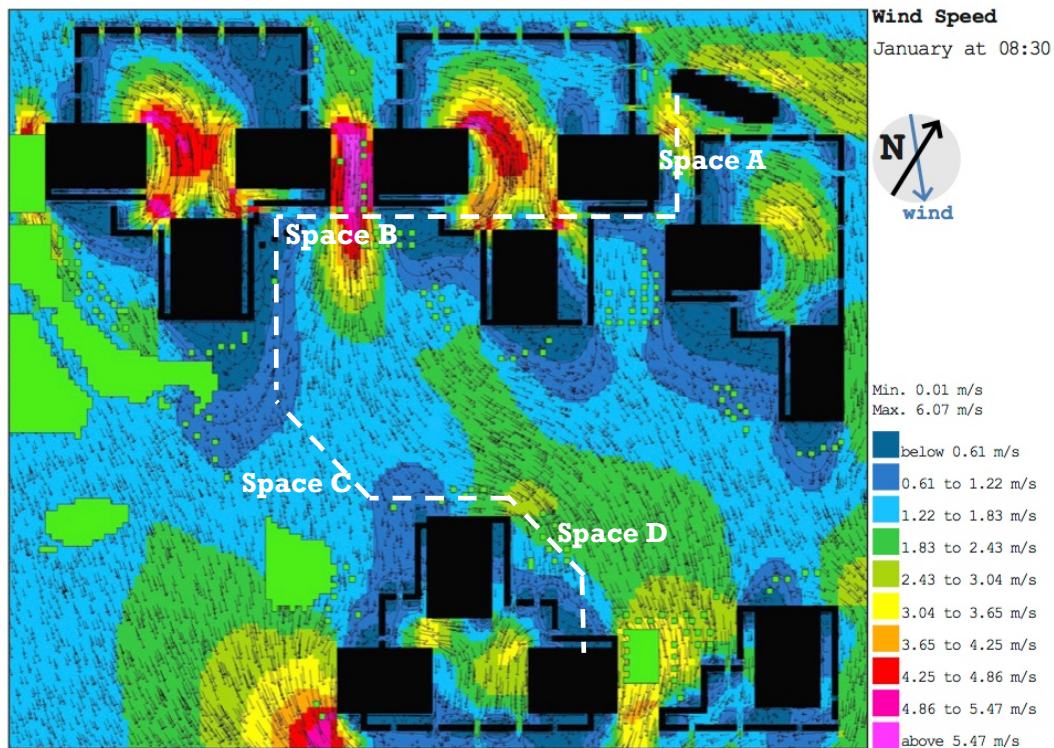


Figure 69 Wind speed, January at 8:30

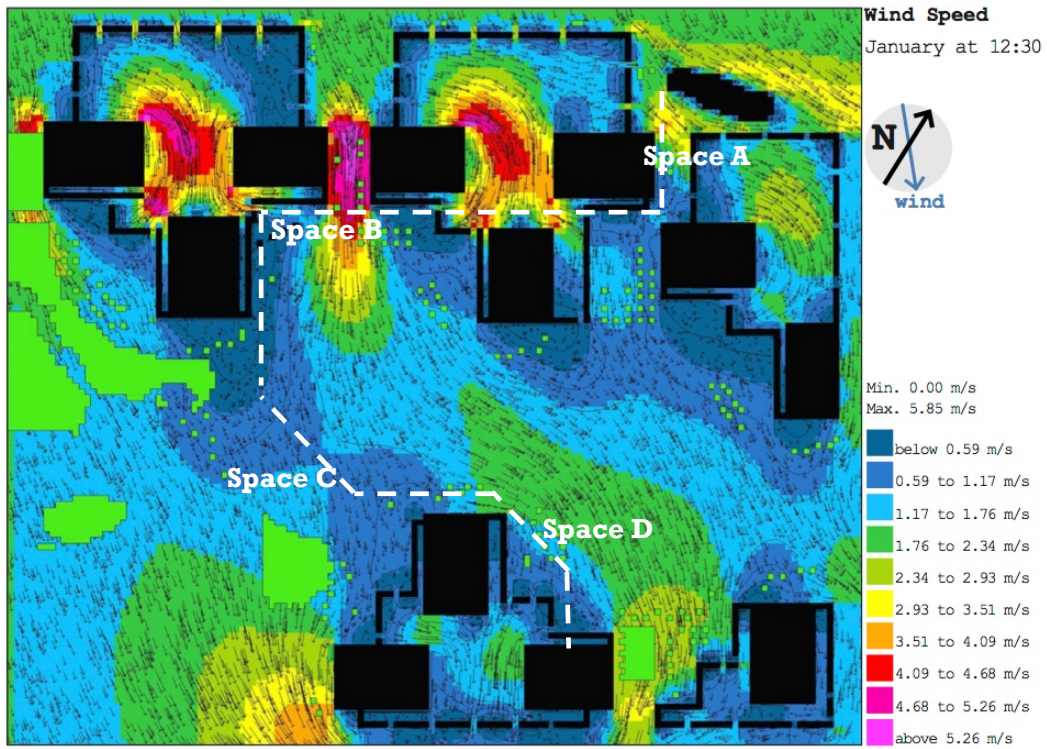


Figure 70 Wind speed, January at 12:30

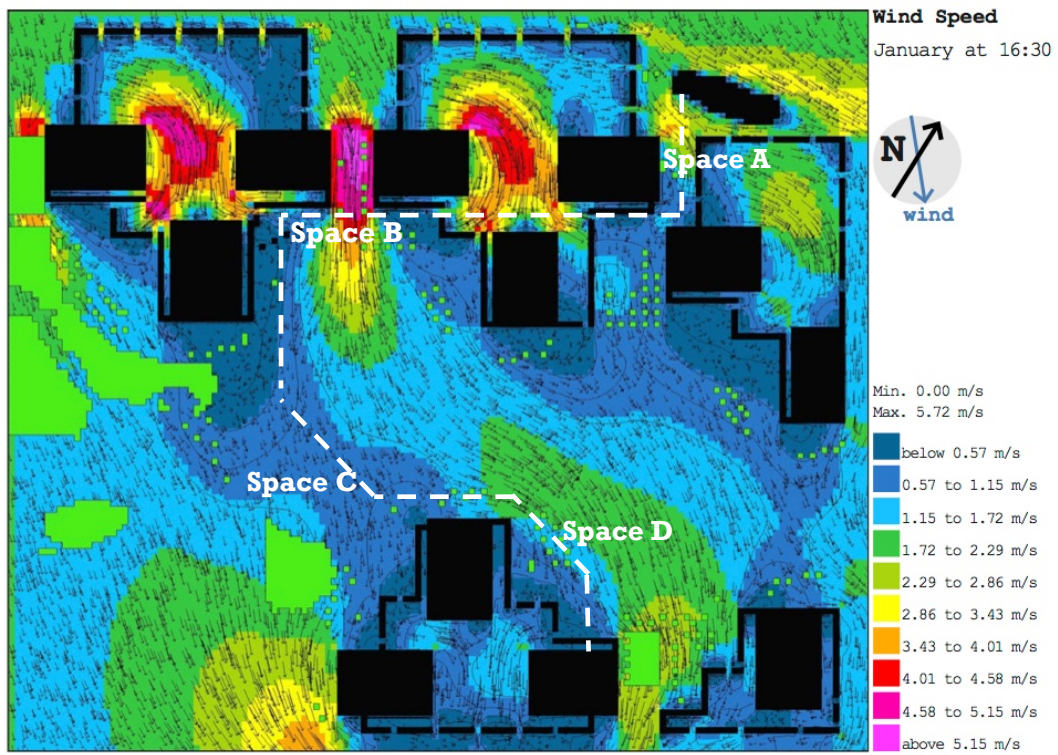


Figure 71 Wind speed, January at 16:30

The PET values attained by the simulations is a reconciliation of the previously demonstrated parameters T_a , MRT and V. During the morning time the PET values ranged between 21.4° and 38.5°C (Figure 72), 32.9° and 58.2°C during midday (Figure 73) and between 32.1° and 50.4°C during the late afternoon (Figure 74). The morning period was considered the most pleasant compared to the other two timings of the day. Differences between the PET values during midday and later afternoon were insignificant. Yet the distribution through the site was remarkable due to the sun angle. Shade proved to have a strong influence on the comfort values besides, wind. The turbulences caused at building corners has influenced the PET values even within non-shaded areas. It is remarkable that the highest PET values are seen at areas with lowest wind speed and lack of shade. This is expected.

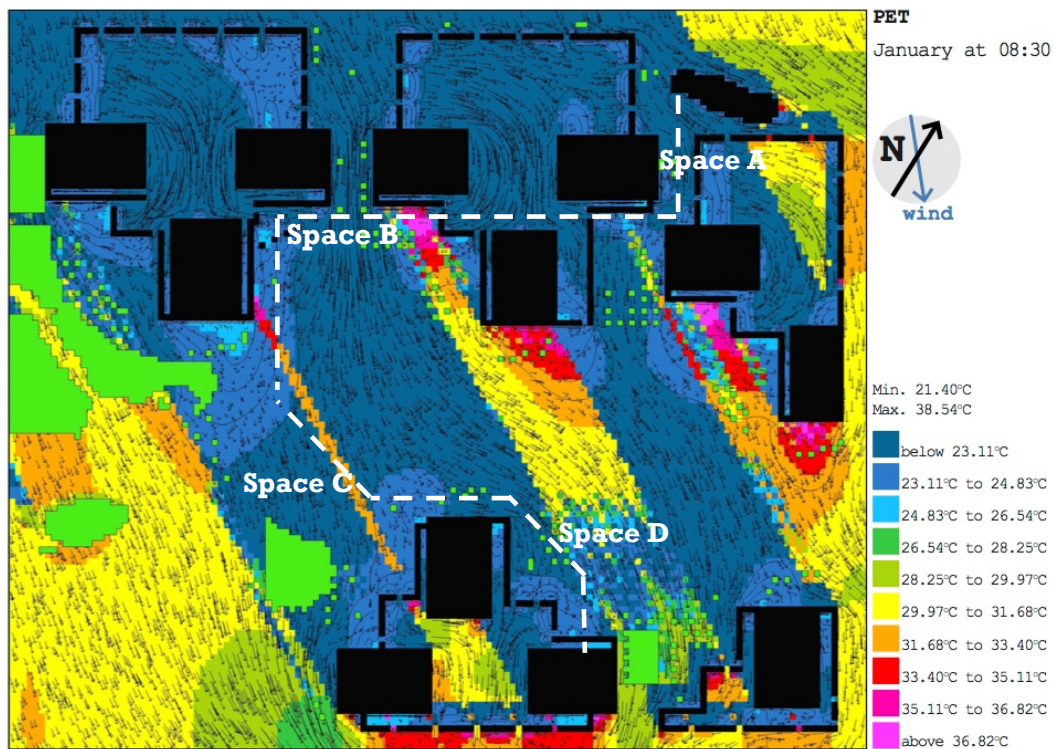


Figure 72 PET, January 8:30

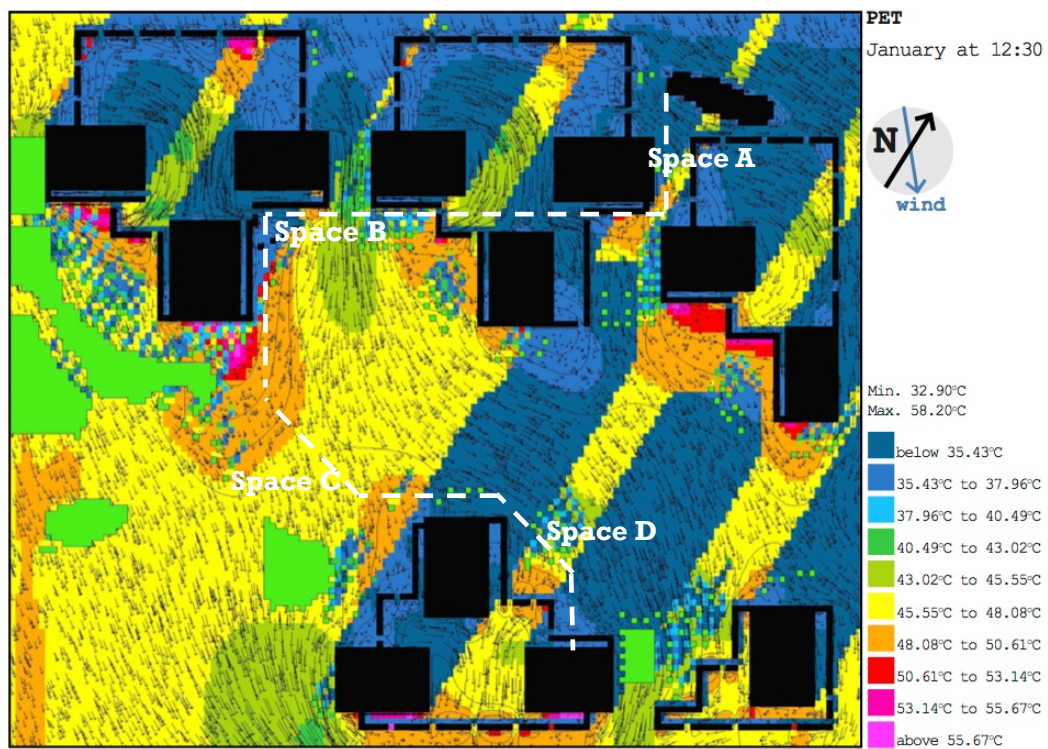


Figure 73 PET, January 12:30

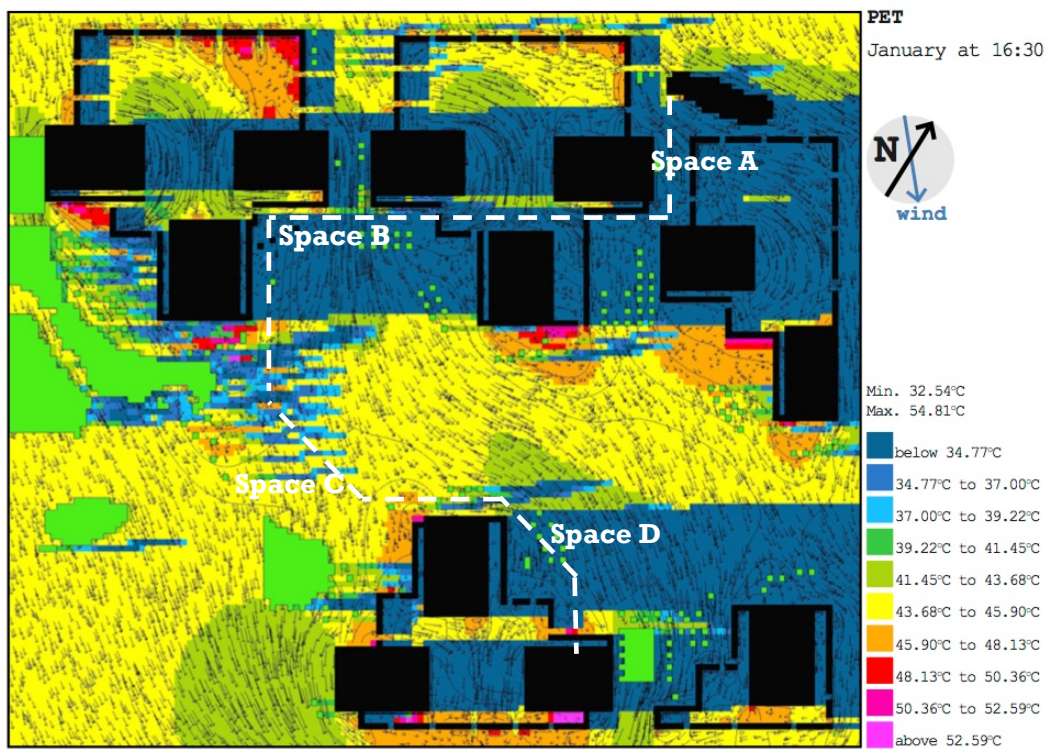


Figure 74 PET, January at 16:30

6.6.2. The warm period (April)

During the morning time the air temperature ranged between 27.2^o and 28.2^oC (Figure 75), 32.4^o and 34.9^oC during midday (Figure 76) and between 33.9^o and 35.6^o during the late afternoon (Figure 77). The average temperature throughout the day was 31.4^oC. The maximum temperature value was recorded during the afternoon 35.6^oC and the minimum value during the morning was 27.2^oC.

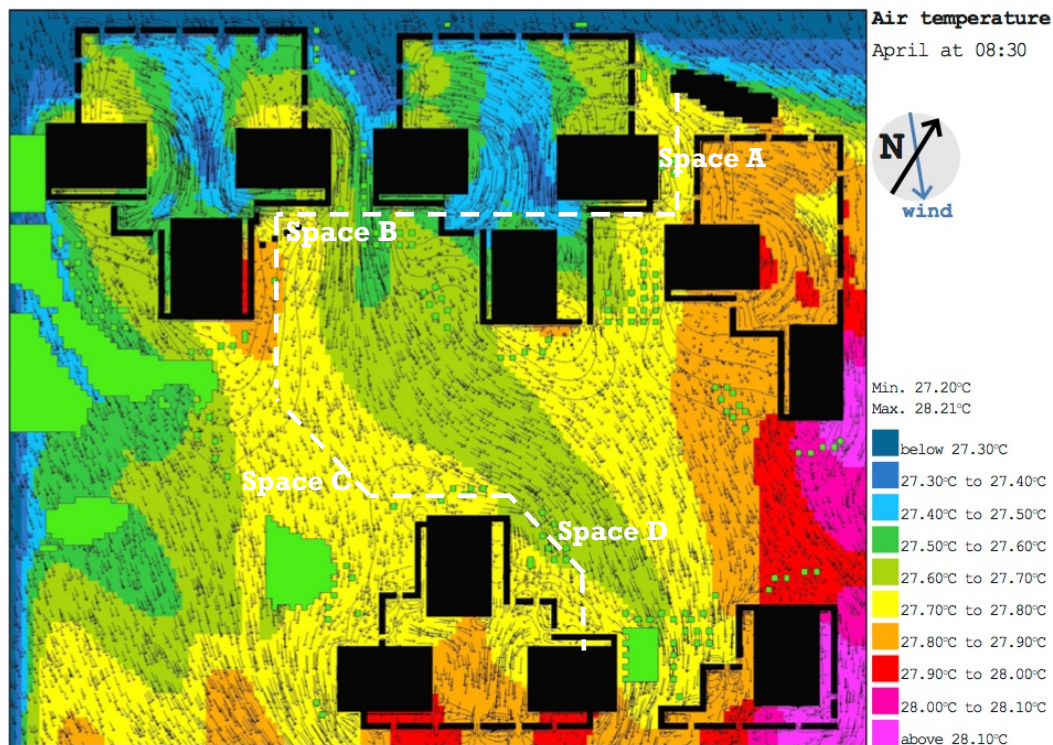


Figure 75 Air temperature, April at 8:30

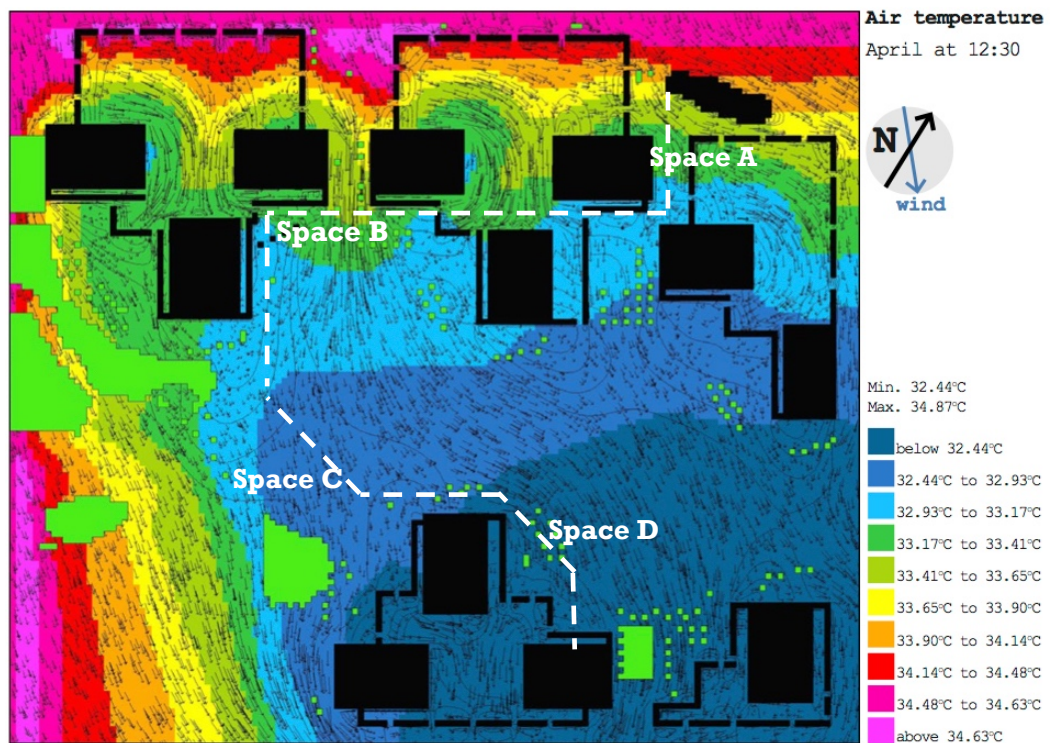


Figure 76 Air temperature, April at 12:30

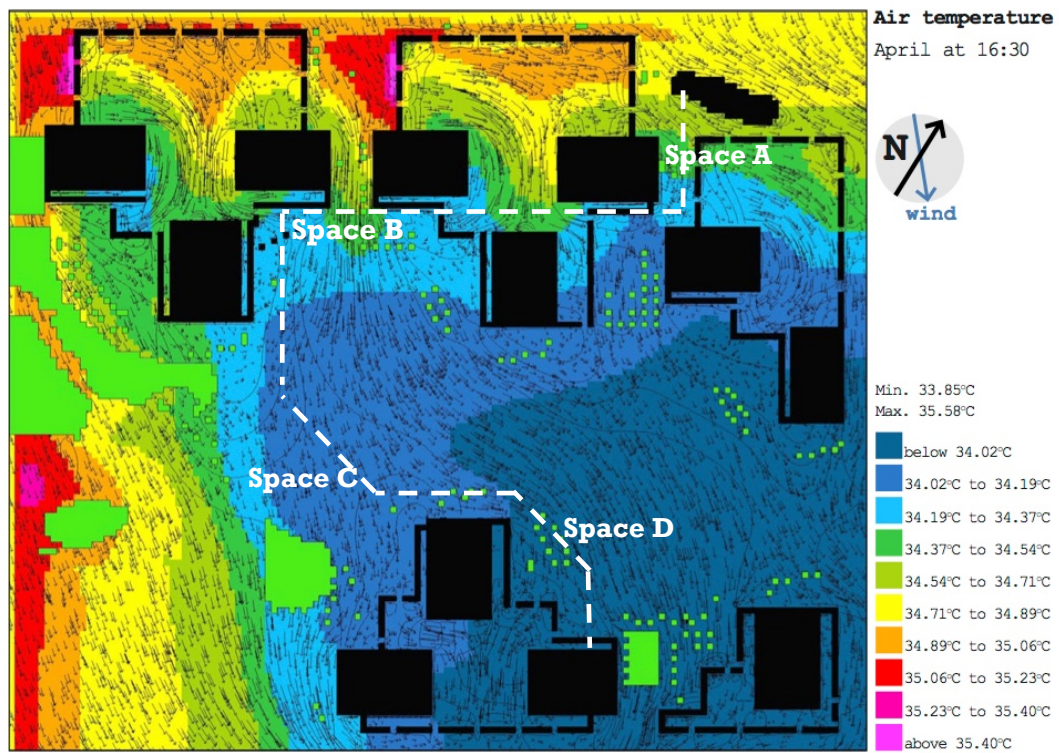


Figure 77 Air temperature, April at 16:30

During the morning time the MRT ranged between 29.6⁰ and 61.8⁰C (Figure 78), 45.7⁰ and 65.5⁰C during midday (Figure 79) and between 40.4⁰ and 69.5⁰C during the late afternoon (Figure 80). The average MRT throughout the day was 49.5⁰C. The maximum value was recorded during the afternoon reaching 69.5⁰C which is due to the highest solar radiation levels. The minimum value was recorded during the morning was 29.6⁰C.

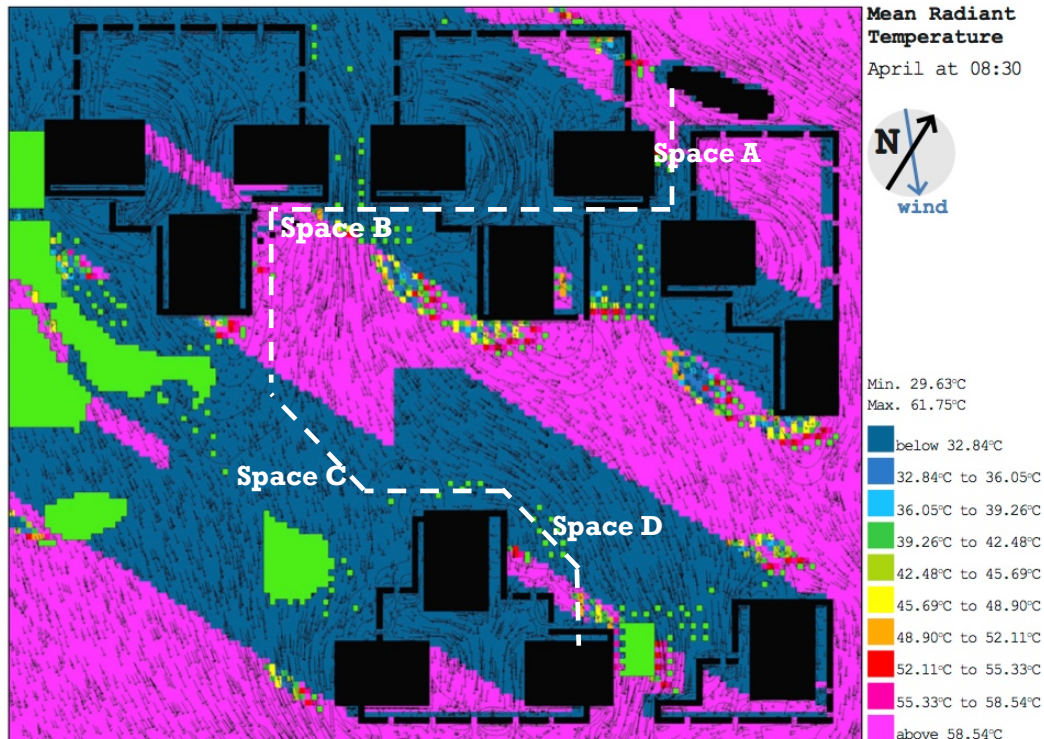


Figure 78 MRT, April at 8:30

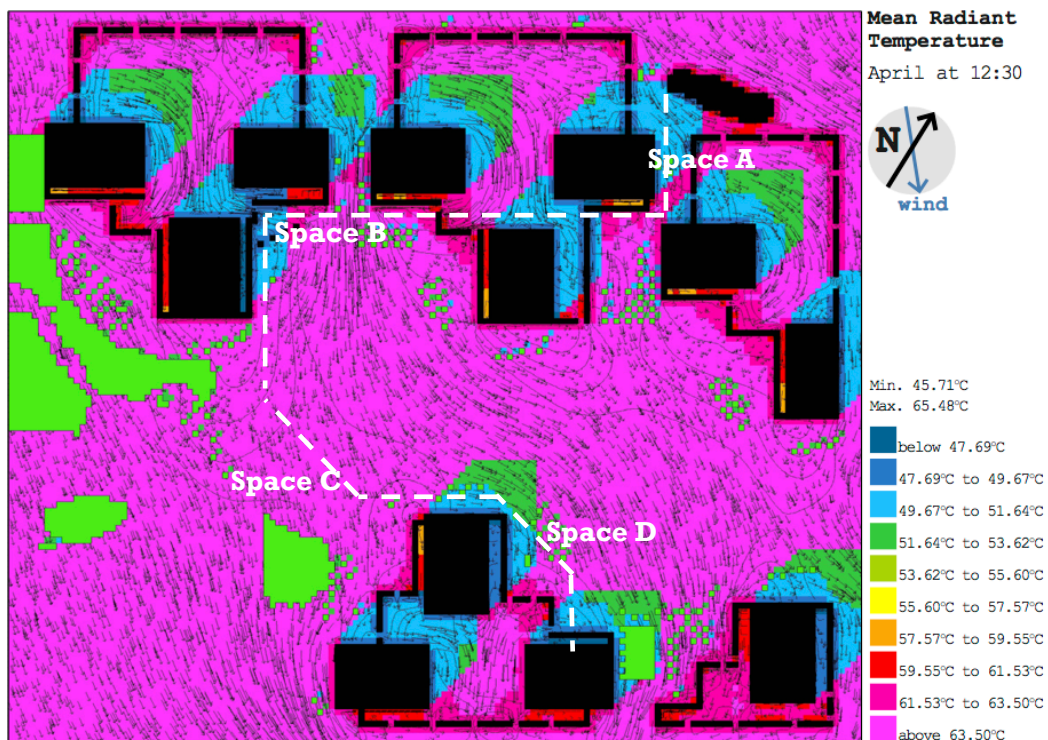


Figure 79 MRT, April at 12:30

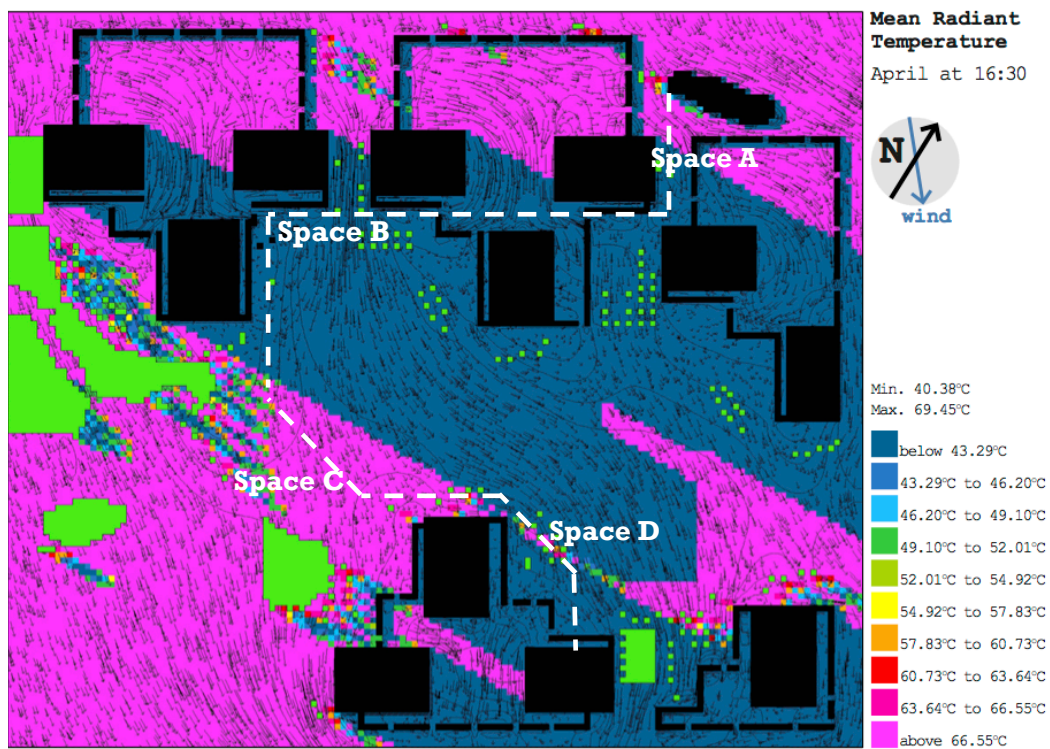


Figure 80 MRT, April at 16:30

During the morning time the wind speed values ranged between 0 and 6m/s (Figure 81), 0 and 5.6m/s during midday (Figure 82) and between 0 and 5.4m/s during the late afternoon (Figure 83). The maximum values of wind ranged between 5.4 and 6m/s also recorded between the two buildings parallel to the wind direction due to the tunnelling effect. Typical to the wind behaviour in January, a turbulence effect was caused inside the parking garages due to the orientation and location of openings. This explained the reason for the rise in air temperature carried from the adjacent warmer spaces.

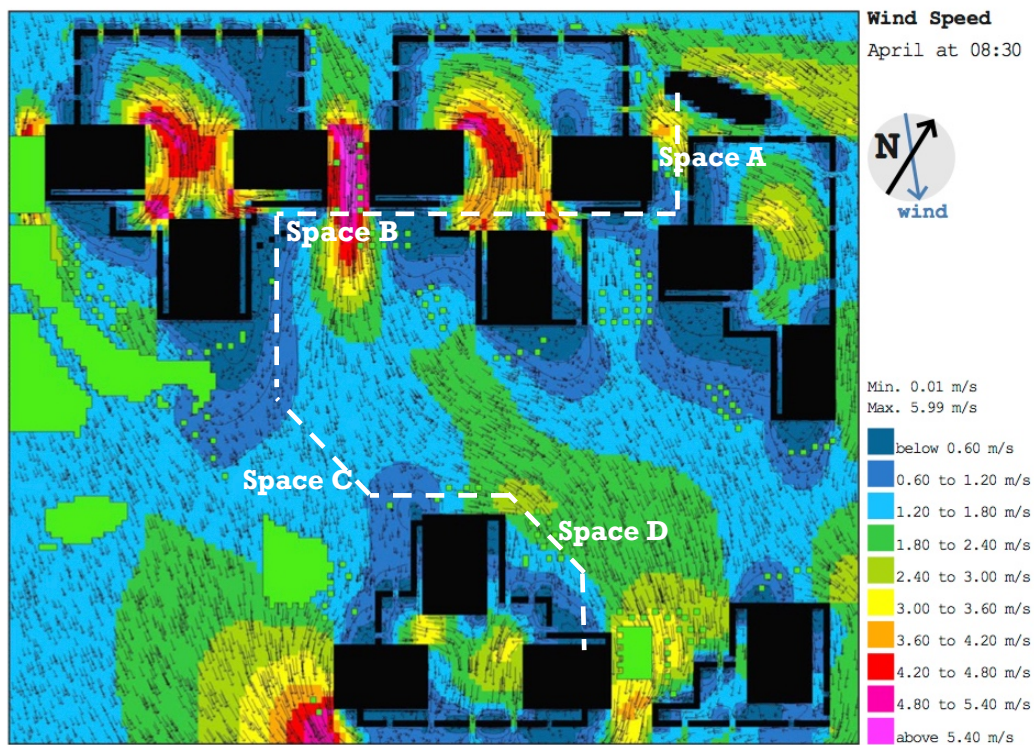


Figure 81 Wind speed, April at 8:30

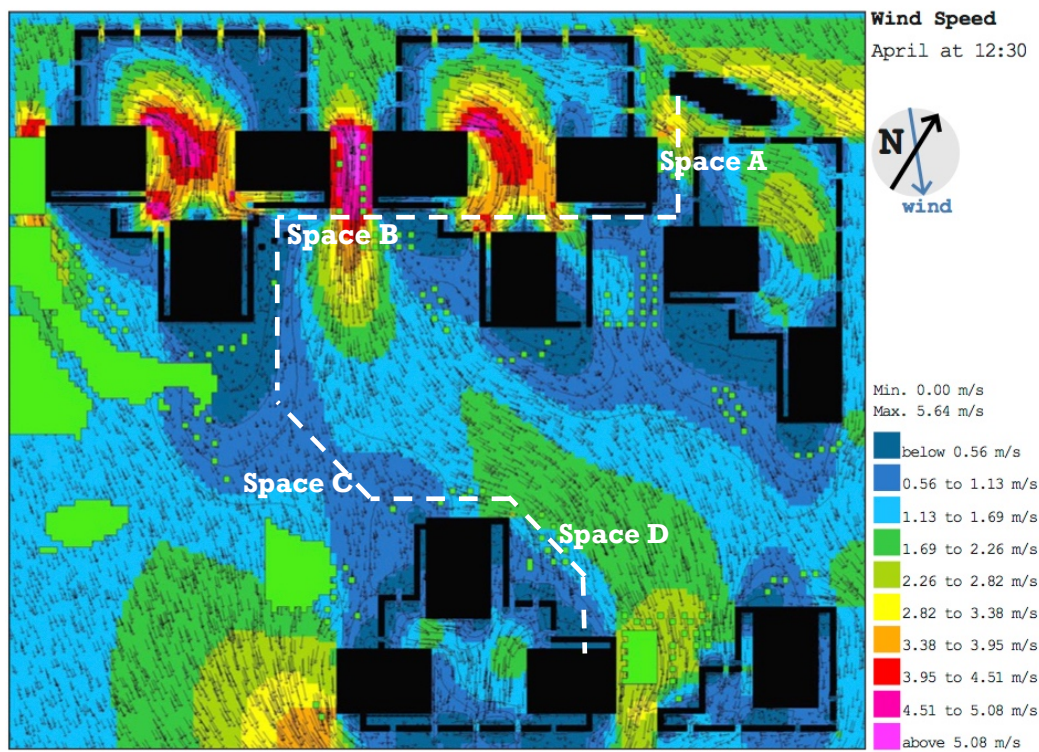


Figure 82 Wind speed, April at 12:30

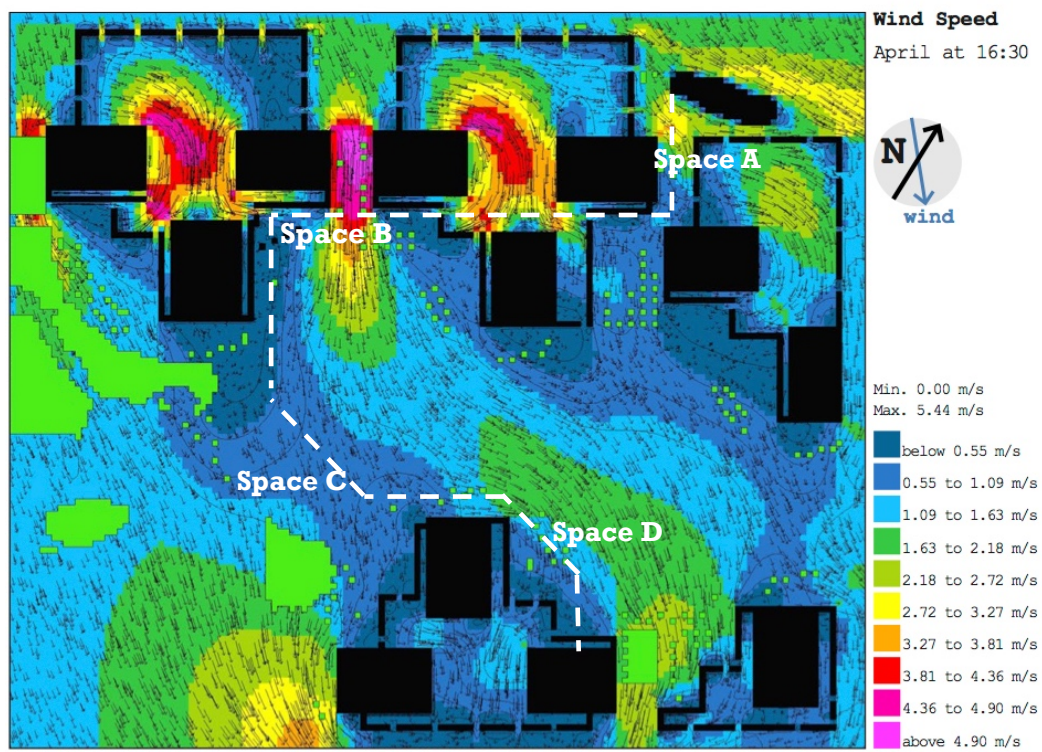


Figure 83 Wind speed, April at 16:30

During the morning time the PET values ranged between 22.8° and 52.8°C (Figure 84), 36.7° and 56.2°C during midday (Figure 85) and between 35.3° and 58.6°C during the late afternoon (Figure 86). The morning period was considered the most pleasant compared to the other two timings of the day. Differences between the PET values during midday and later afternoon were insignificant. Yet the distribution through the site was remarkable due to the sun angle. Shade proved to have a strong influence on the comfort values besides, wind. The turbulences caused at building corners has influenced the PET values even within non-shaded areas. Again, the highest PET values are seen at areas with lowest wind speed and lack of shade.

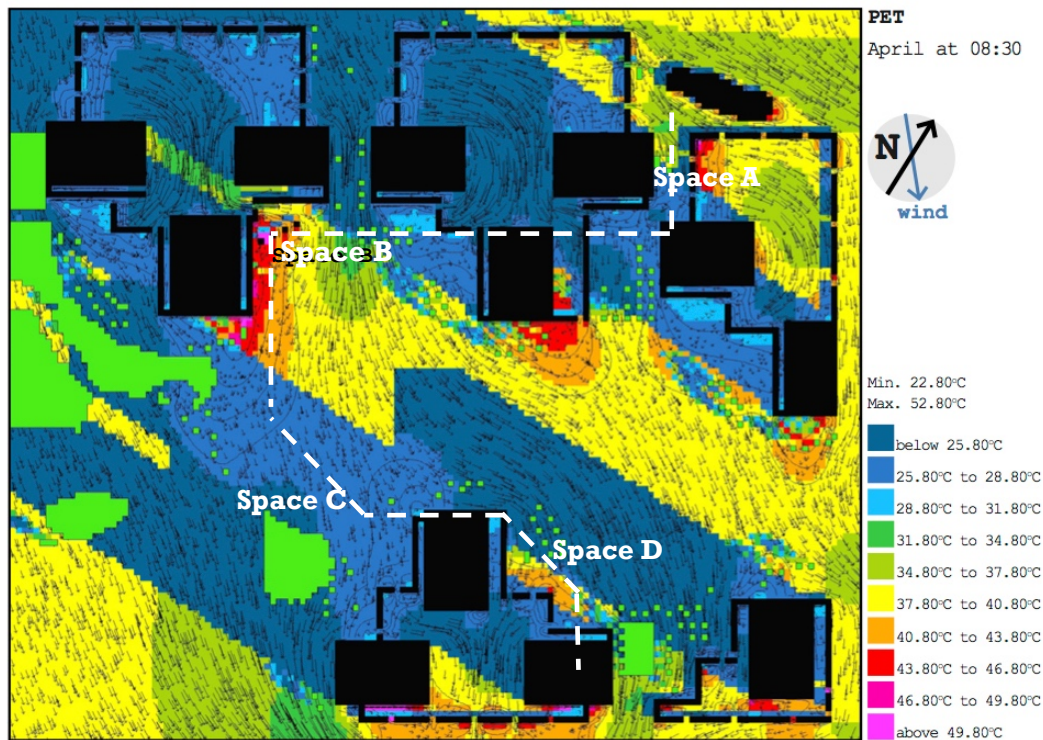


Figure 84 PET, April at 8:30

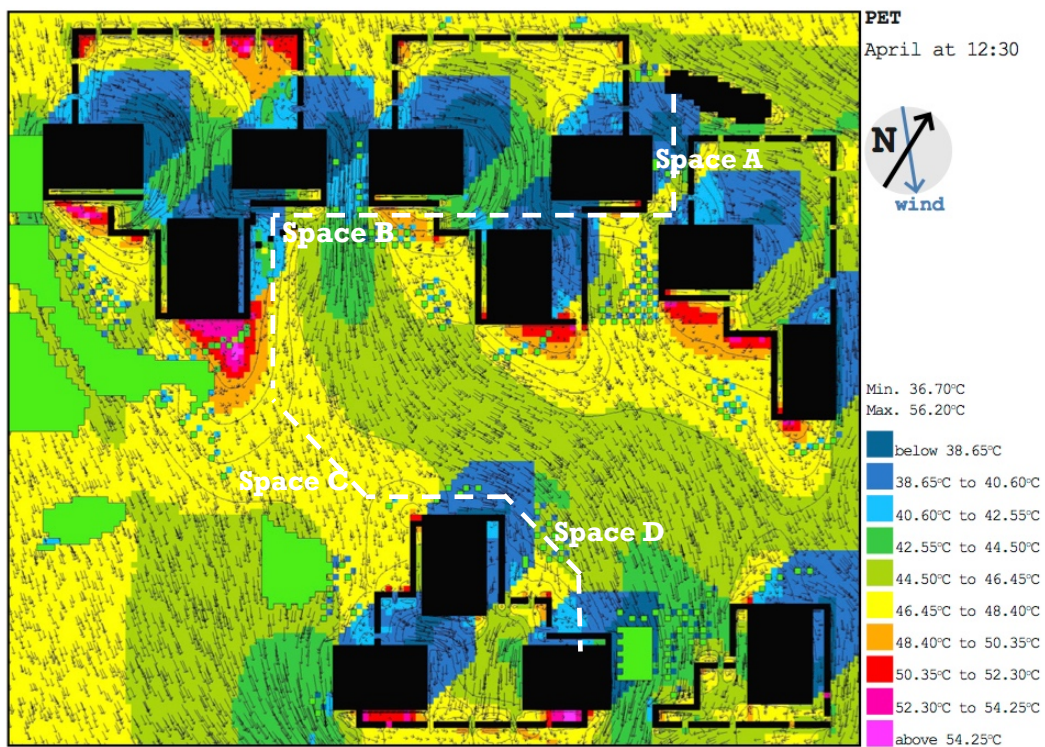


Figure 85 PET, April at 12:30

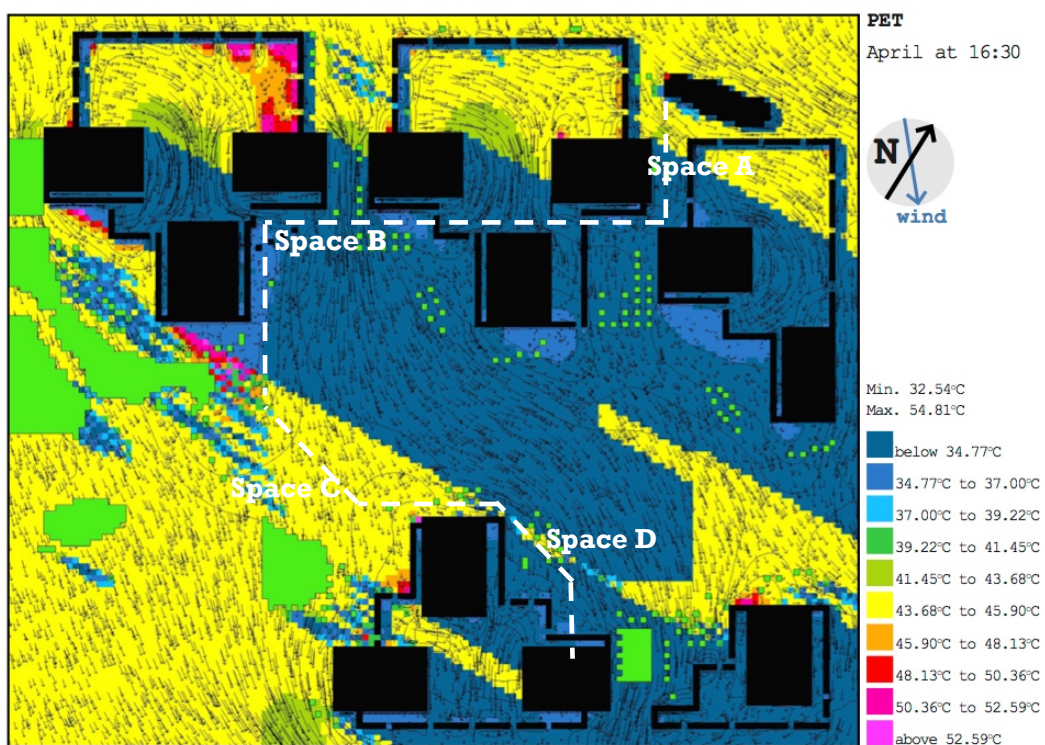


Figure 86 PET, April at 16:30

6.6.3. The hot period (September)

During the morning time the air temperature ranged between 27.1⁰ and 28.1⁰C (Figure 87), 32.4⁰ and 34.7⁰C during midday (Figure 88) and between 33.7⁰ and 35.3⁰ during the late afternoon (Figure 89). The average temperature throughout the day was 31.2⁰C. The maximum temperature value throughout the day was recorded during the afternoon 35.3⁰C and the minimum value during the morning was 27.1⁰C.

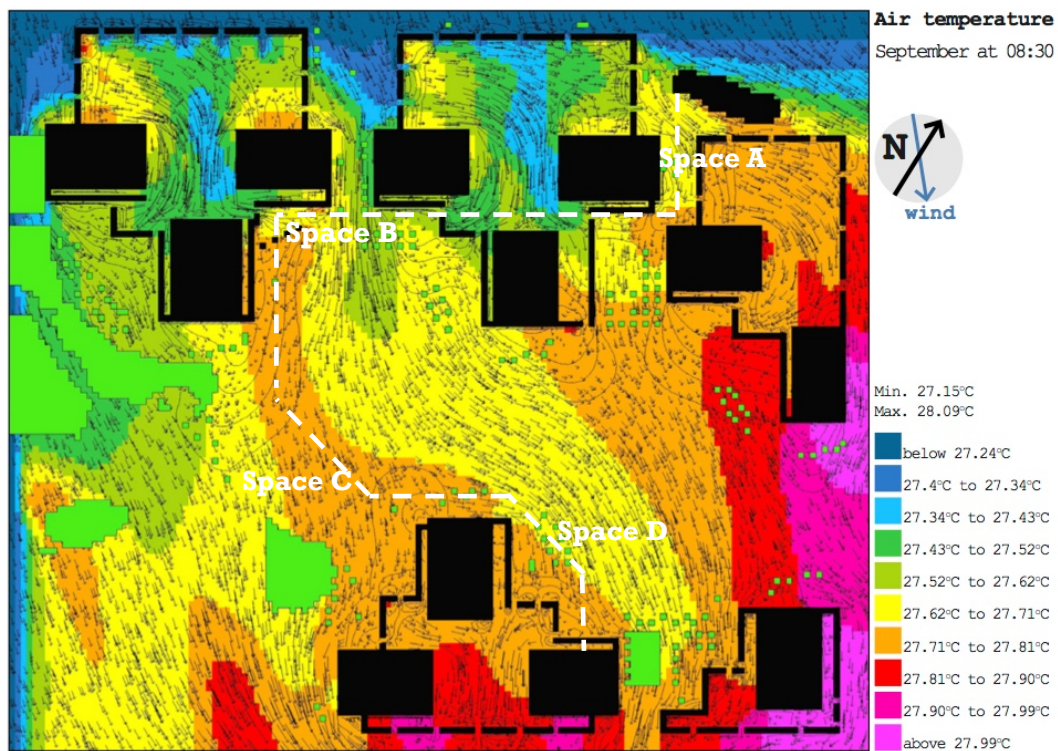


Figure 87 Air temperature, September at 8:30

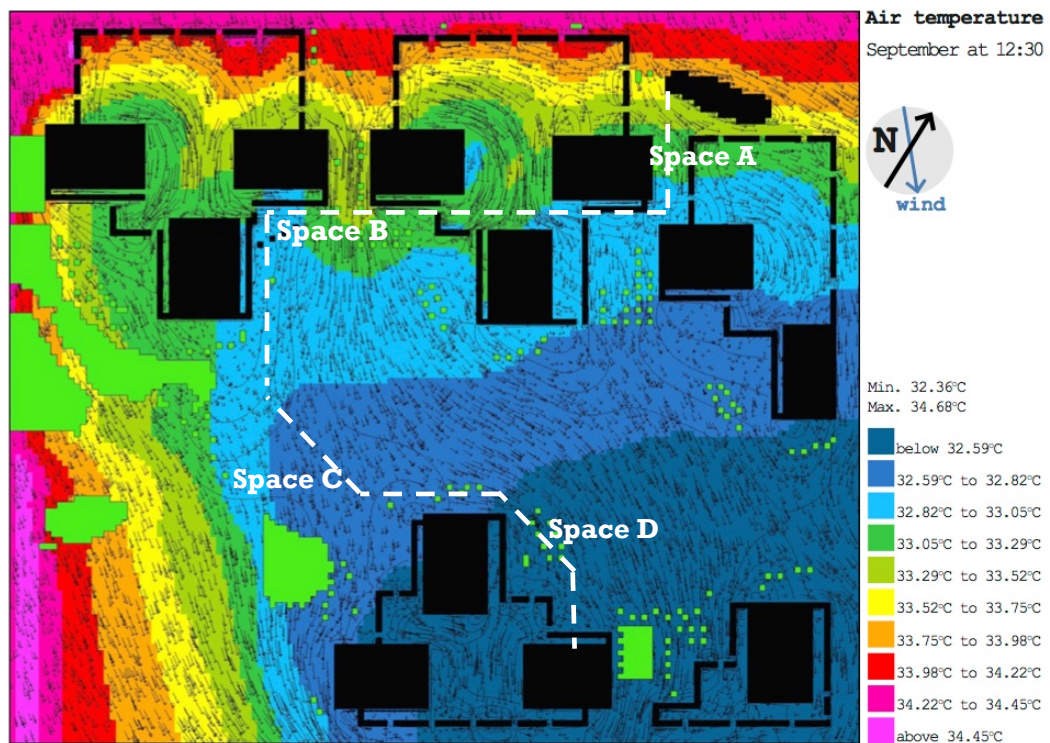


Figure 88 Air temperature, September at 12:30

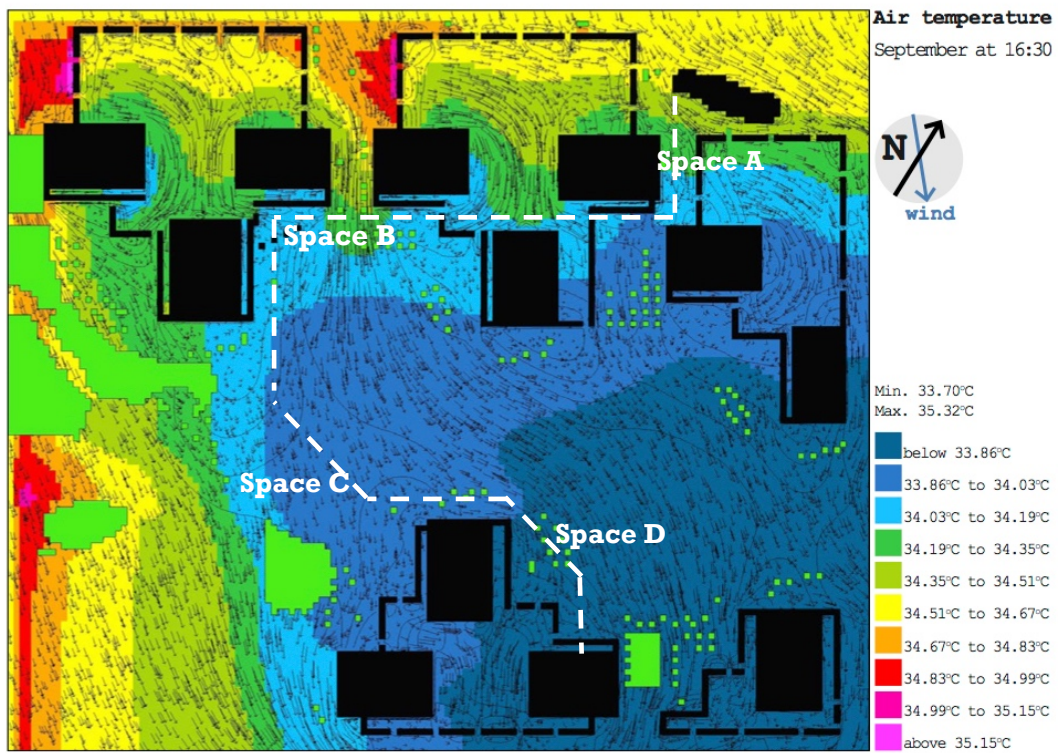


Figure 89 Air temperature, September at 16:30

During the morning time the MRT ranged between 28.7° and 60.1°C (Figure 90), 44° and 67.7°C during midday (Figure 91) and between 37° and 64.5°C during the late afternoon (Figure 92). The average MRT throughout the day was 48.1°C. The maximum value was recorded during midday reaching 67.7°C which is due to the highest solar radiation levels. The minimum value was recorded during the morning 28.7°C.

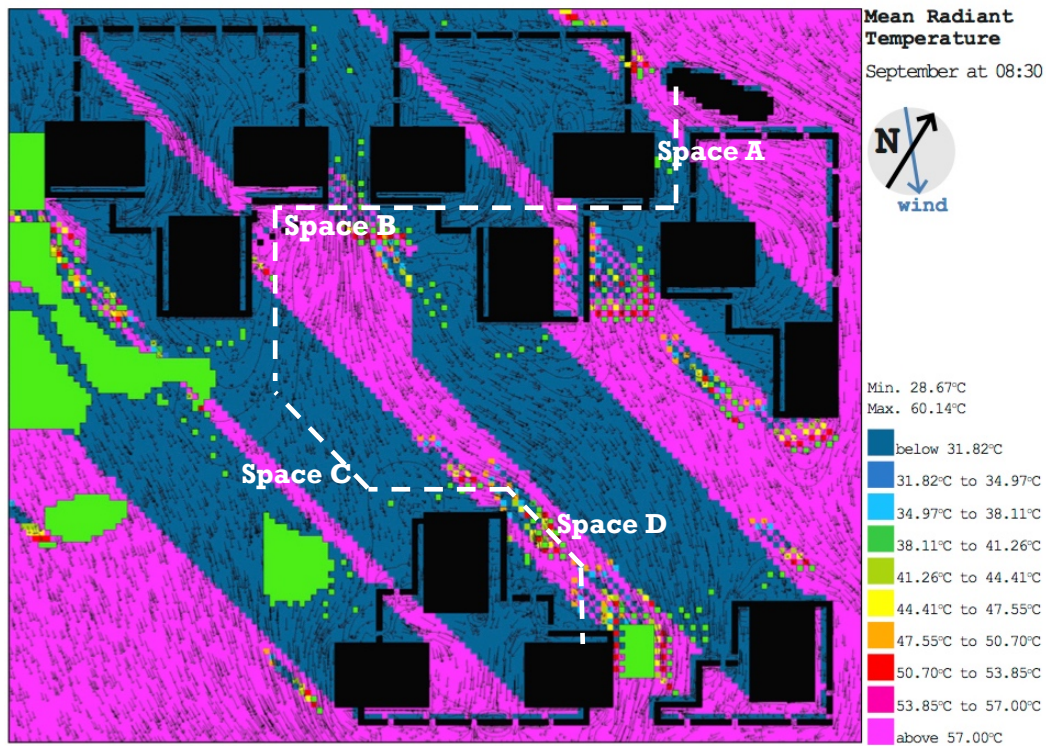


Figure 90 MRT, September at 8:30

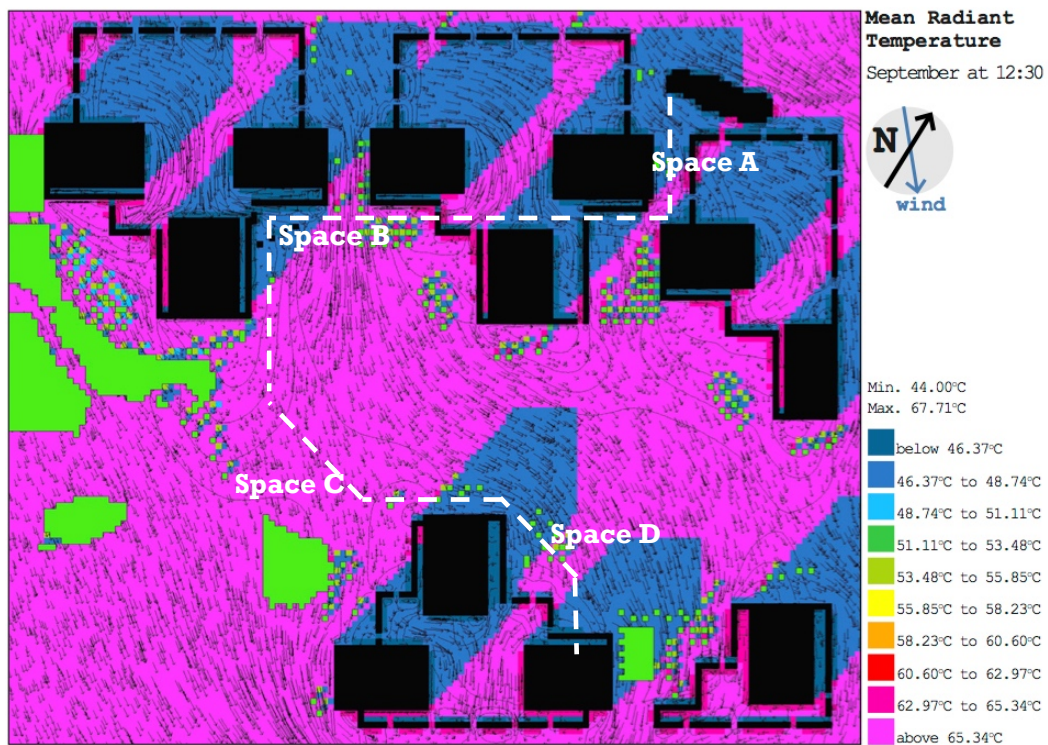


Figure 91 MRT, September at 12:30

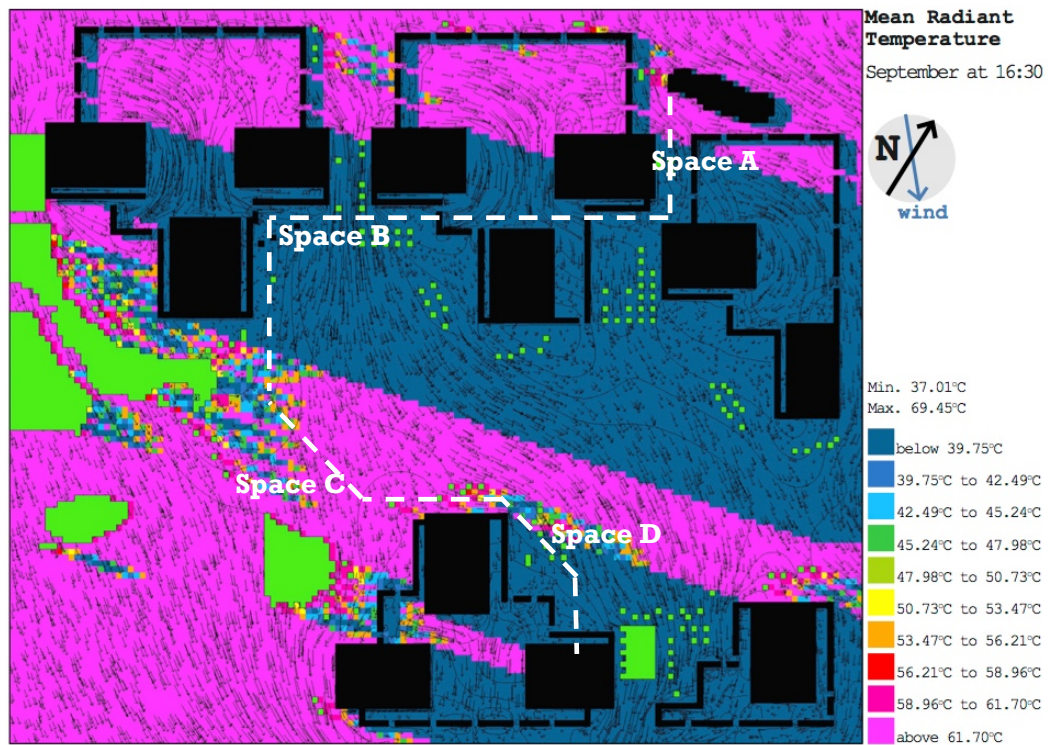


Figure 92 MRT, September at 16:30

During the morning time the wind speed values ranged between 0 and 6m/s (Figure 93), 0 and 5.7m/s during midday (Figure 94) and between 0 and 5.5m/s during the late afternoon (Figure 95). The maximum values of wind ranged between 5.5 and 6m/s were recorded between the two buildings parallel to the wind direction. Such composition caused a tunnelling effect which was consistent throughout the day and influenced a large area of the site. Areas where there was a staggered layout of buildings reduced the wind speed dramatically. Inside the parking garages a turbulence effect was caused due to the orientation and location of openings. When correlating such finding with the rise of the revealed air temperature, it explained the reason why those spaces were warmer, and at sometimes when compared to other non-shaded open spaces.

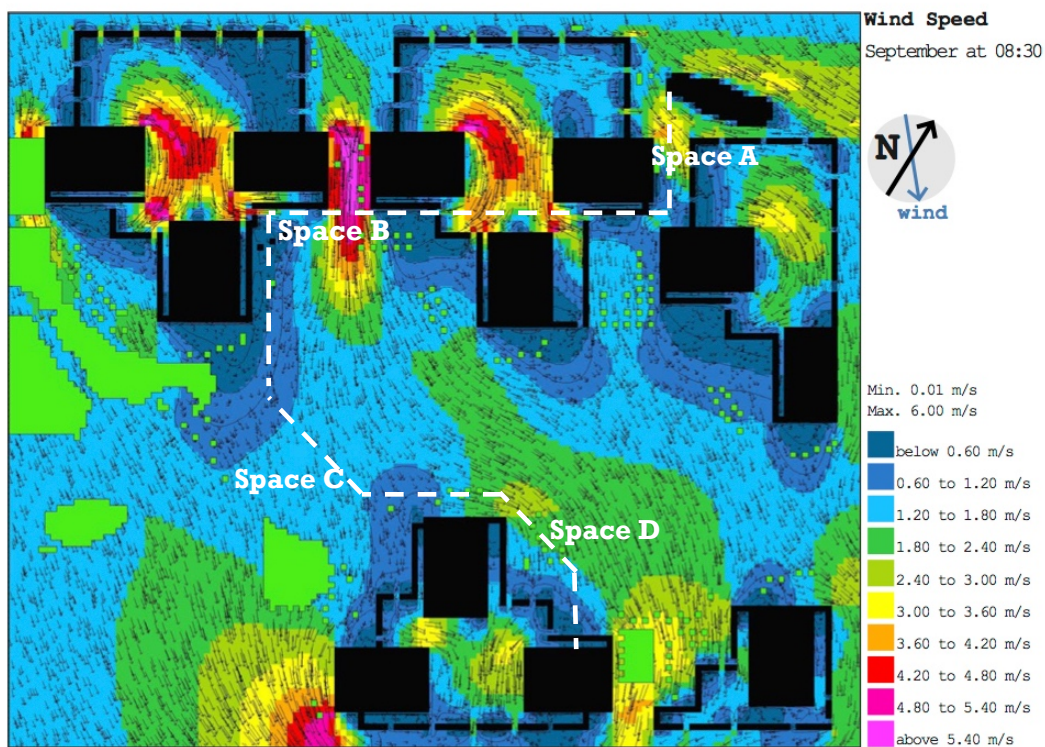


Figure 93 Wind speed, September at 8:30

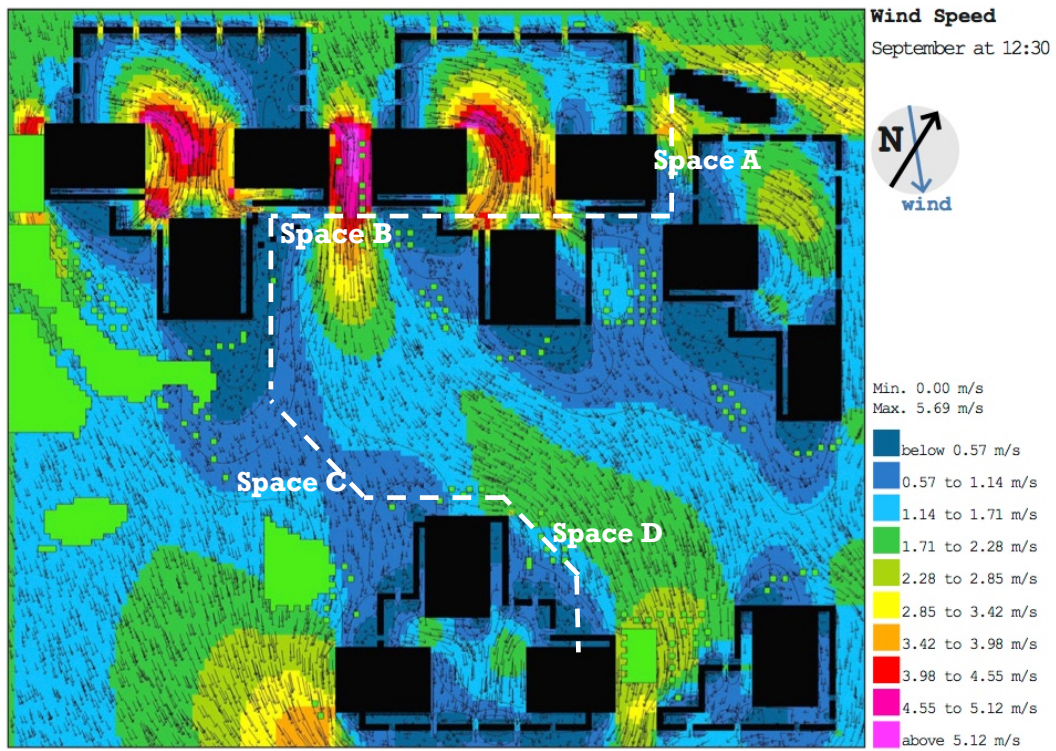


Figure 94 Wind speed, September at 12:30

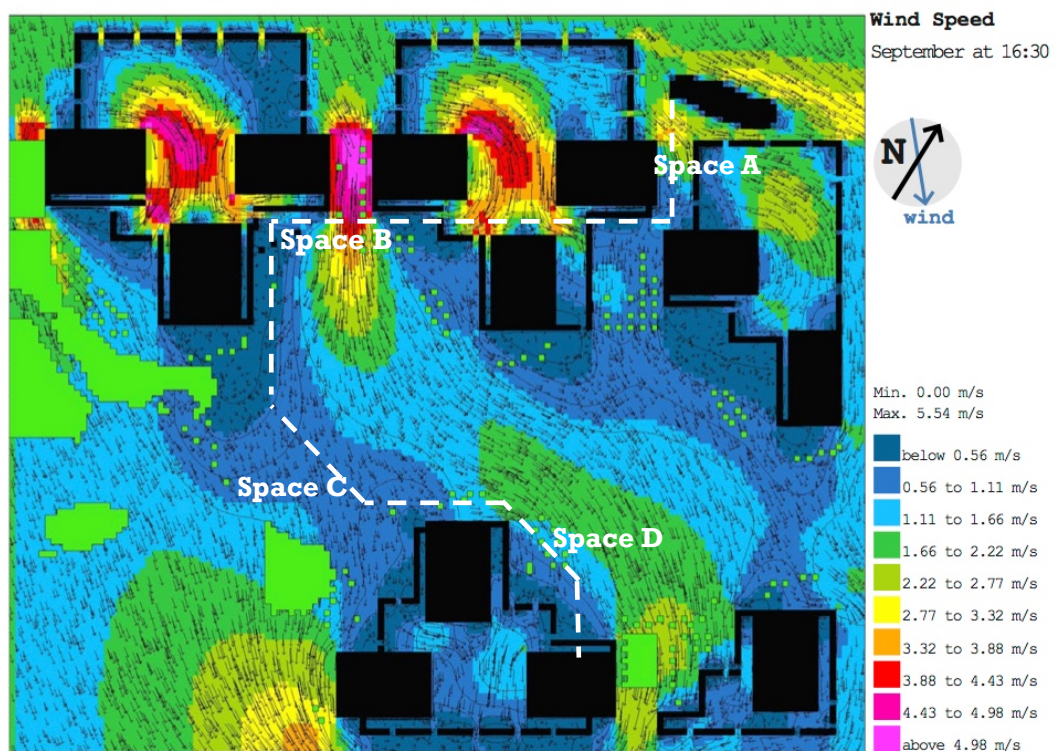


Figure 95 Wind speed, September at 16:30

During the morning time the PET values ranged between 22.8⁰ and 51.6⁰C (Figure 96), 35.3⁰ and 58⁰C during midday (Figure 97) and between 33.9⁰ and 54.6⁰C during the late afternoon (Figure 98). The morning period was considered the most pleasant compared to the other two timings of the day. Differences between the PET values during midday and later afternoon were small. Yet, the distribution of values through the site was remarkably dependent upon shade, since it has a strong influence on the comfort values besides. Besides, the turbulences occurring at building corners has influenced the PET values even within non-shaded areas. Expectedly, the worst PET values are seen at areas with lowest wind speed and lack of shade.

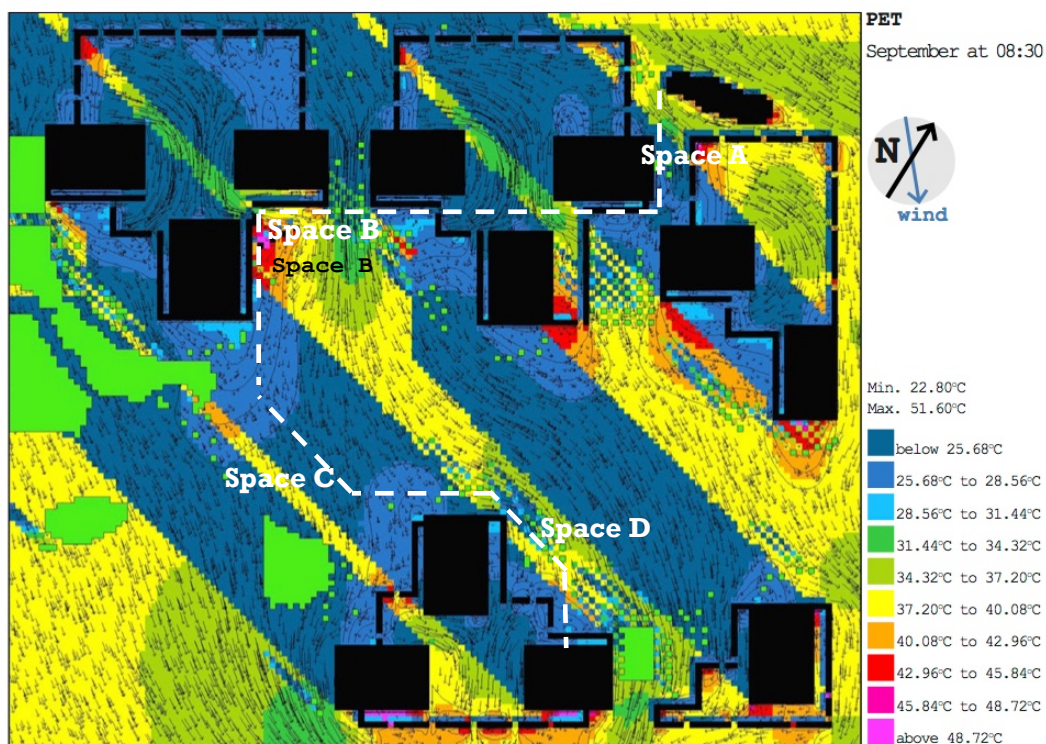


Figure 96 PET, September at 8:30

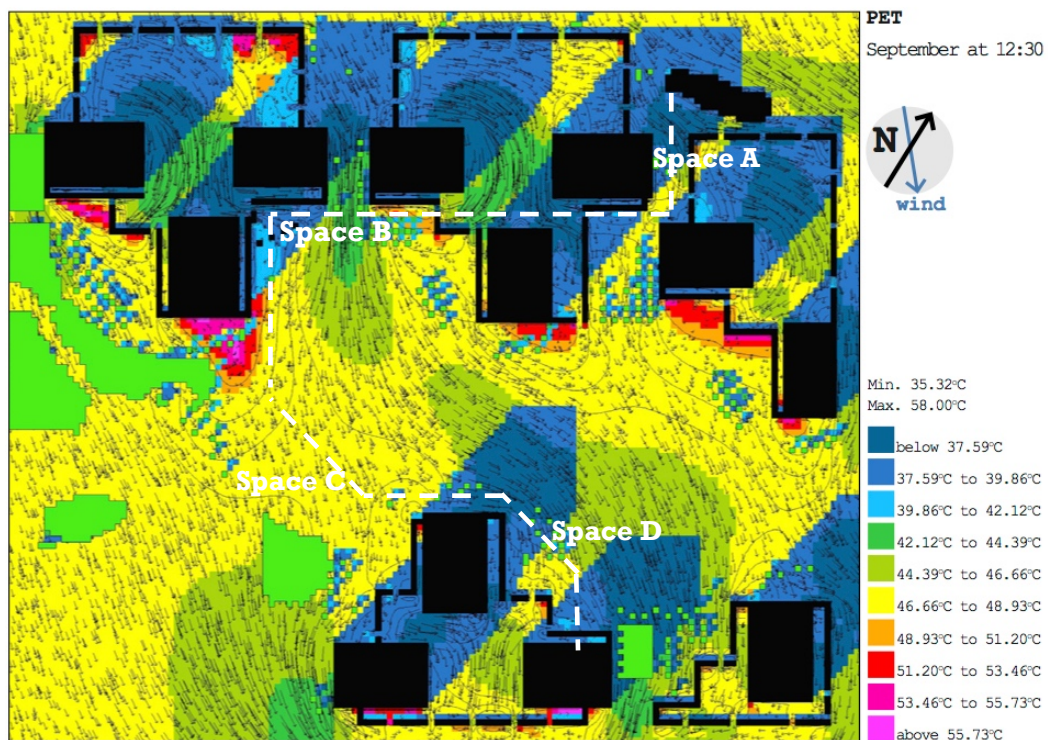


Figure 97 PET, September at 12:30

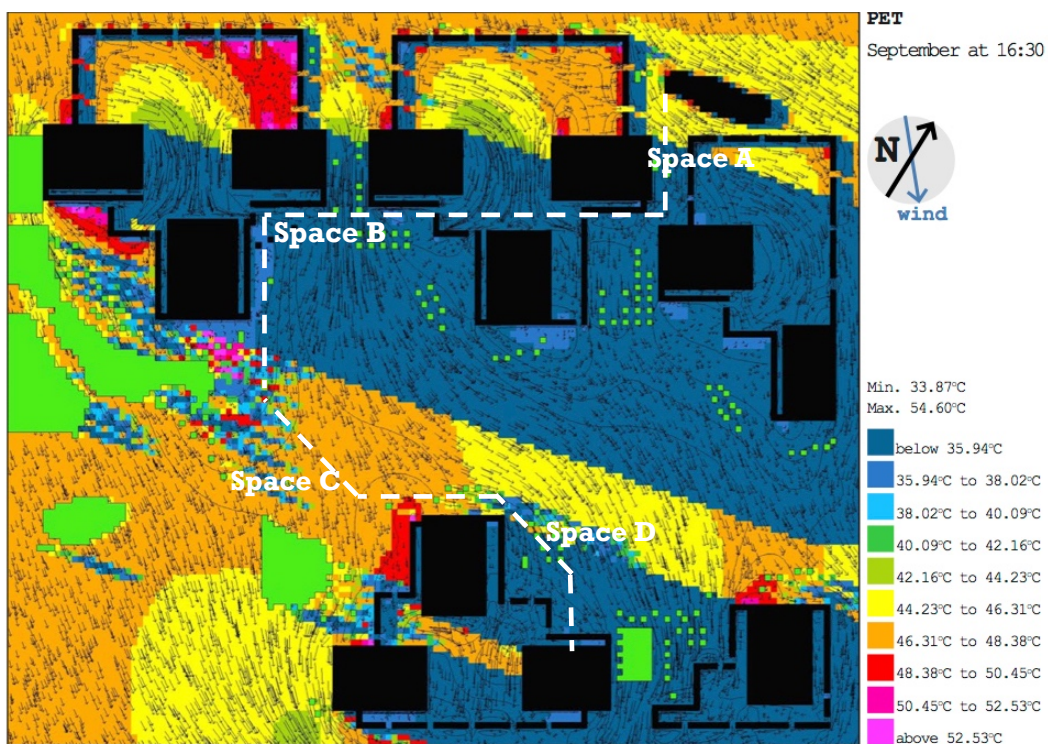


Figure 98 PET, September at 16:30

6.6. Conclusion

The results from the microclimatic simulations had helped understand the behaviour of certain parameters questioned during the long-term environmental monitoring. In general, it was noted that the behaviour of the microclimatic parameters analysed, T_a , V and MRT was consistent with slight variations throughout the year during the same time of the day. During January, April and September, the maximum air temperature values were always recorded during the afternoon followed with a slight increase during midday. Mornings were always the coolest time of the day when compared to the other timings. In January and September, the MRT values were highest during midday, and during the afternoon in April. The diurnal range (difference between the maximum and minimum values of T_a) was the highest during April followed by September, followed by January, with a value of 8.4K, 8.2K and 7.9K respectively. It is noteworthy that constantly, the minimum values recorded during the three periods were shaded. This highlights the effectiveness of shade to reduce the T_a as the weather conditions gets warmer. This range was substantially wider and inversed when looking at the MRT values. The diurnal range was the highest during January followed by April, followed by September, with a value of 46.2K, 39.9K and 39K respectively.

The wind patterns and wind speeds were influenced greatly by the urban layout. The tunnelling effect accelerated the wind between buildings. Such behaviour highlighted a potential for orienting higher wind speeds accelerated by building layout to ventilate and cool spaces along pedestrian's journeys particularly those that suffer from the lack of shade. This notion has inspired the design intervention proposed in Chapter 7.

The thermal comfort, denoted by PET, was worsened at areas which lacked shade and wind speeds below 1.0 m/s. The difference between the highest and the lowest PET values were 35.2K in September 35.8K in April and 36.8K in January, which is due to the diurnal values of T_a during the same months. During the morning time in April and September, PET recorded higher values in Space B, Figure 84 and Figure 96, indicating lower comfort levels. The measured T_a during the environmental monitoring also recorded higher values compared to the other spaces, despite the presence of shade. It was observed that the TSV and TCV of pedestrians when interviewed in this space was one step worse compared to the votes from other spaces at the same timing. This was due to the higher temperatures spreading from the tunnelling effect between the buildings adjacent to the space. This is because the area facing the wind before being accelerated recorded much higher T_a and MRT values. Besides, the turbulence occurring inside the parking garages also provided heat within the space.

PART III: THE PROPOSED INTERVENTION

CHAPTER 7: Thermal Comfort Recovery Conditions

This chapter seeks to reconcile all the different findings from reviewing the literature, the fieldwork investigations and the analytical work that was conducted to improve walkability in urban communities in Dubai. The problem identified in the Introduction highlighted the fact that, as the weather gets warmer, townspeople are increasingly reluctant to walk between utilitarian destinations due to the drop in their thermal comfort level. In many months of the year, fewer people spend time outdoors because it is so uncomfortable. They resume their walking only when the temperature falls.

The multiple approaches chosen for research considered both subjective and objective factors, such as the human parameters and the physical environment. Pedestrians' thermal comfort limits at various times of year were set, identifying the *tolerable* distances that would not deter them from walking outdoors. This has helped to identify the points along many journeys which require a cooling intervention where people could recover from discomfort enough to continue their walk and repeat it next day. The other factor that was investigated was the design attributes of the urban spaces *en route*, which could cool the microclimate and thus influence pedestrians' thermal comfort positively. The sequential transitions of urban spaces and their influence on thermal sensation were the central focus.

This chapter sets out the *recovery conditions* and shows how an intervention, if designed sensibly, and applied to certain locations along a route can improve thermal comfort and thus extend pedestrians' walking distances. The effectiveness and applicability of one such intervention was tested in the local conditions using the microclimatic simulation tool ENVI-met and further recommendations have been proposed.

7.1. The notion of the recovery

In the Oxford Dictionary (Anon, 2017), the word 'recovery' is defined as "a return to the normal state of health of mind or strength". In the context of this research, 'recovery' refers to a return to a neutral or improved state of thermal comfort during a walk. This state influences one's physiological and psychological sensations through providing certain microclimatic conditions. The results are specific to pedestrians and their thermal comfort levels as they walk along a route.

After one's body experiences a few minutes' discomfort, one begins to thirst for relief, to restore the former level of thermal comfort. The effect of the discomfort from the microclimatic conditions may be offset by restorative physical spaces. This makes the unfavourable non-shaded and non-ventilated spaces no longer problematic; if managed sensibly these areas would preserve walkability. When the

urban design cannot preserve it, applying the proposed intervention would extend the tolerable distances between facilities. This is discussed in more detail below.

7.2. Improving thermal comfort

The proposed concept is characterized by couple of factors that can boost pedestrians' satisfaction and therefore it could be embodied in one or more spaces along a pedestrian route. However, its effectiveness depends on two main features. The first is the location where it is applied, which depends on the thermal conditions of the antecedent space. A recovery space should be created soon after discomfort has been triggered; it should not become intense. The second concerns the physical characteristics of the space in terms of shading and ventilation, which have been shown repeatedly to boost both thermal sensation and thermal comfort. These are passive design elements that allow the thermal sensation to return to a better state through the efficient use of shade and wind, as detailed below.

The idea of recovery presented in this chapter depends on improving thermal comfort through physiological and psychological factors (Figure 99). Findings from the present study suggest that planning one or more recovery spaces along a pedestrian route could extend the *tolerable* distances people walked and thus they could endure walking for more days in the year. Such an extension could not be achieved by providing continuous shade or wind as they walked. The combination of improved thermal sensation and the lifting of heat stress, however, significantly raise the level of thermal comfort. Each of the aspects is related to the main factors of thermal comfort, physiological and psychological, as seen in the figure below. Next, these factors are described explicitly.

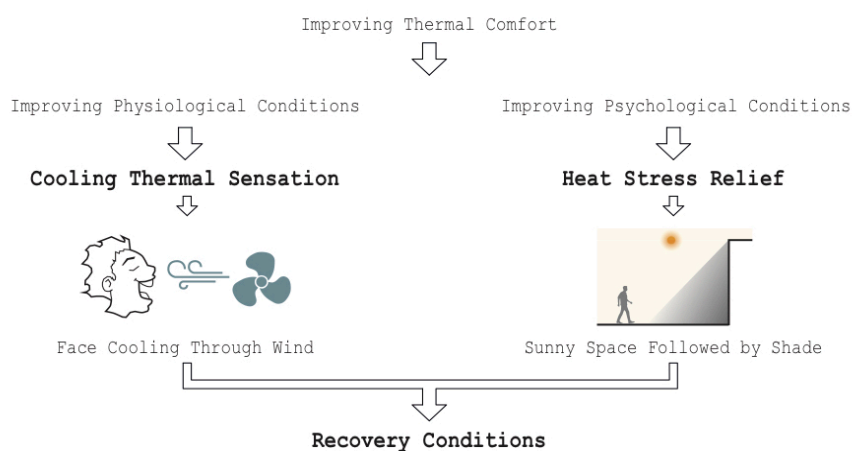


Figure 99 An approach to improving thermal comfort through recovery factors

7.2.1. Cooling thermal sensation

The first pillar supporting the proposed notion is cooling the thermal sensation. It involves enhancing the thermal sensation through a thermoregulatory process of locally cooling the face (Figure 99). The face is a very effective area for local cooling due to the large number of cold thermoreceptors underneath the skin. Besides, the presence of sweat promotes loss of heat as it evaporates, cooling the skin surface and delivers a cooling sensation to the whole body.

Results from the thermal walks conducted at three different times of year (described fully in section 5.3 above) revealed that a wind moving at 3.2m/s improved pedestrians' thermal sensation significantly. This was observed in two cases: first, on relatively windy days, pedestrians felt cooler as the wind accelerated. The wind provided a better thermal sensation when it touched uncovered parts of the body, such as the lower arm, face and neck. Second, when wind was induced by a fan blowing 50cm away at 3.2m/s and directed at the face. It improved the thermal sensation by evaporative cooling through moisture on the surface of the pedestrians' skin.

7.2.2. Heat stress relief

As discussed earlier in Chapter 2, the removal of heat stress produces a pleasant and comfortable feeling, called the "Kuno effect" which lasts several minutes (Potvin 2010). During the fieldwork conducted in the present research, the very similar effect on the pedestrians was predominantly verified during the thermal walks. It is the heat stress relief, which was most effective in warm climatic conditions.

Along the thermal walks, as the subjects in the field experiment moved to the shade, they felt an instant improvement in their thermal comfort. However, in the thermal sensation such improvement was not instant. This is due to the psychological factors influencing comfort: that people felt relieved when they moved into the shade, even when it is only slightly cooler (Figure 99). If the pedestrians walked along that same shaded space for a long time instead of moving into it from a sunny one, their thermal sensation would drop gradually as they did so and it would not be perceived as a relief. This also is due to the fact that people perceive shade spaces to be cooler than sunny ones even when the thermal conditions of these spaces are not necessarily better.

According to these findings, the perception of sunny spaces in an urban environment can benefit if the route then leads to a recovery space. However, it is essential to allow enough time for the body to recover after the transition. The concept presented here suggests that the only feasible way to encourage walkability in urban areas in warm conditions is to make shading and ventilation for all outdoor spaces discontinuous.

7.3. Guidelines and application strategies

There are numerous ways in which the notion of a recovery factor could be contextually designed to fit an urban area and ensure its functionality. This study does not seek to provide a specific design intervention, for no fixed design could fit everywhere. Urban design features and elements need to be contextual to fit and function in an urban area. Instead, the research provides a design methodology, including a set of principles and guidelines. This methodology should be tailored and developed further by architects and urban designers who wish to encourage walkability in the city.

Exploiting shade and wind are the most effective strategies suggested for improving pedestrians' thermal comfort in the climate of Dubai. Shade should not block the path of the wind, since wind ventilation is the primary way of compensating for the high humidity levels. Therefore, the guidelines below focus on providing shade, capturing and accelerating wind and bringing them both to the pedestrians' level; these are the main feature of the proposal described next.

7.3.1. Comfort declining zones

In a master plan, there are certain areas that are considered problematic from a climatic point of view. For instance, hot spots are areas that lack solar control and thus accumulate heat, which can be more critical if they face the direction of the wind. The microclimatic conditions of adjacent spaces can be influenced negatively by a warm breeze if it blows from there, even if shade and suitable materials are provided. This case was encountered during fieldwork with 'Space B'. Therefore, the problematic areas, named *comfort reducing zones*, along pedestrian's journeys, should be identified so that they can be equipped with interventions that would maintain the level of thermal comfort.

Along a pedestrian's journey, the *comfort reducing zone* is a space with worse microclimatic conditions than other spaces along the same journey, for example, with higher air and mean radiant temperatures, lower wind speeds, higher humidity levels or any combination of these. The optimum way to identify these spaces is to run a microclimatic simulation analysis, such as ENVI-met. The microclimatic parameters are extracted by the software through visual maps that allow critical comparisons to be made at any time of the day and year. The main advantage of this method is that it allows assessment of the whole site on a larger scale.

In Chapter 6, the ENVI-met simulations run for the urban district JLT revealed a problematic area, which also was shown in the field surveys presented in Chapter 5 to impair thermal comfort. The path along which pedestrians walked to the mosque, work and metro at three different times every day: 8:30, 13:30 and 16:30 (Figure 100 and Figure 101), recorded higher air temperature and mean radiant

temperature values than the surrounding spaces. This was validated by the long term environmental monitoring conducted for Space C.

Accordingly, the PET values extracted by ENVI-met revealed lower comfort levels. The antecedent space, named Space B, also measured in the fieldwork, revealed high air temperature values compared other spaces, despite the presence of shade for most of the day. It was found that the high air temperature values were due to the effect of stagnation. Therefore, Space B, which is the antecedent space for a *comfort reducing zone*, does not aid thermal comfort along this journey (Figure 102).



Figure 100 Image of the pedestrians walking to the mosque in JLT at midday along the sunny path



Figure 101 A closer image of the pedestrians walking to the mosque in JLT at midday along the sunny path



Figure 102 Image of the comfort reducing zone where pedestrians in JLT walk between the metro station and the office building, troubled by the lack of shade.

7.3.2. Location and frequency

The findings from this research deal with the *comfort reducing zones* as areas with the potential to extend the length of the journeys that pedestrians can make if *recovery factor* are applied. The recovery improves the thermal comfort levels by providing shade and wind. Shade and wind screens – the form of which is described in more detail below – should be located in the centre or at the end of the sunny path to obtain the stress relief effect.

Next, the time spent walking before and after this zone should be identified, to work out the remaining distance along the journey and judge whether one or more recovery space is needed. In locating the wind and shade screens, the designer should take into account on the time that pedestrians tolerate walking in each climatic period; the screens should be closer to the ends of the route than to the middle.

It should be noted that recovery factors may be added more than once along the route, depending upon the length and frequency of the comfort reducing zones. But if thermal comfort is to be improved several times, fluctuations in the thermal transitions should be subliminal, as described in the literature (see Chapter 2 section 2.3). It is expected that the effectiveness of recovery declines with repetition and that the number of effective repetitions is limited. However, this point requires further investigation. It seems to be the case that if one reaches a certain state of discomfort – as the time of exposure increases – passive cooling improvements tend to lose significance (the law of diminishing returns) and people require much longer times for recovery, which conflicts with the principle of recovery spaces.

Few relevant findings were identified during the thermal walks and the interviews on the influence of shade and its repetitiveness along the pedestrian's journeys. These findings help urban designers understand the right mixes of sun and shade distribution (shade being a dominant recovery strategy), which allows them to design outdoor walkways more efficiently to improve comfort. Figures 104-106 represent these strategies in a conceptual way, using trees as the source of shade that does not necessarily be the only method in an urban area.

For instance, Figure 103, shows the higher effectiveness of the length shade. Short shaded spots do not improve pedestrian's thermal sensation as they need few minutes to cool down depending upon their previous exposure. Another strategy is avoiding such lengthy non-shaded spaces, as shown in Figure 104, even if recovery is to follow. Long non-shaded areas along the path decline comfort drastically, where comfort recovery becomes unreasonable. Therefore, shaded areas should be designed to reduce the length of non-shaded area.

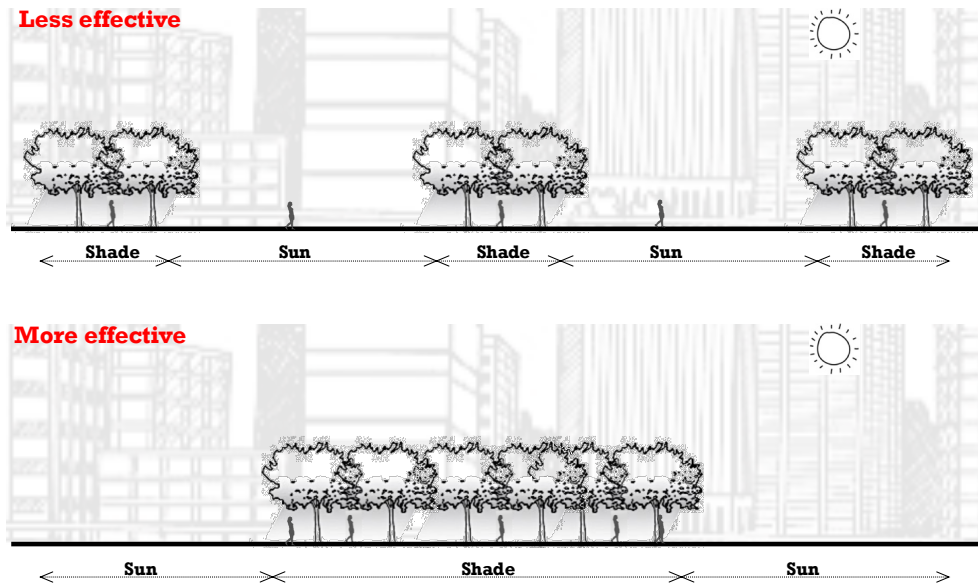


Figure 103 Sketch showing the effectiveness of grouping trees to provide longer strip of shade instead of having short strips that are less effective.

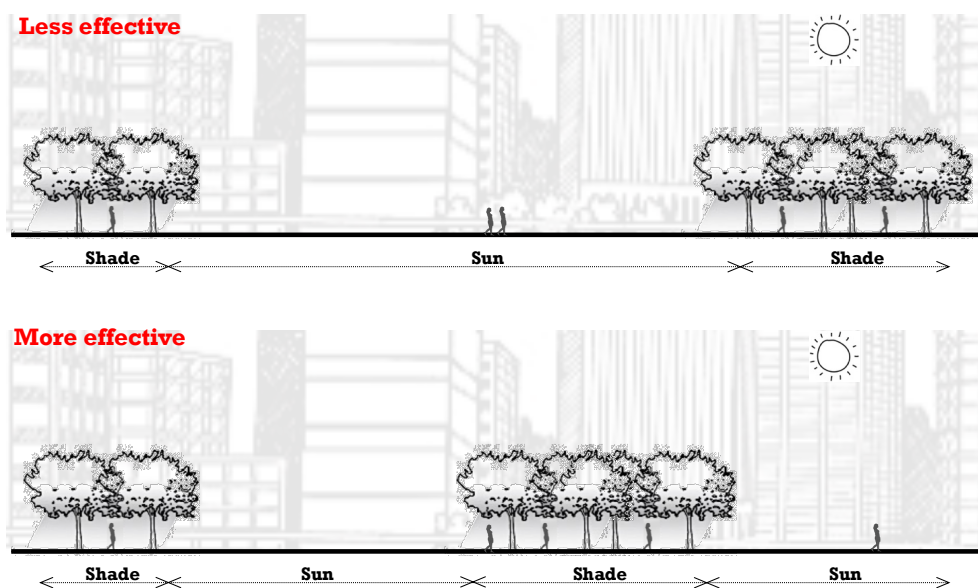


Figure 104 Sketch showing the importance of avoiding lengthy non-shaded strips that would decline comfort drastically.

As the paths gets longer, designing shade and repeating recovery conditions for comfort becomes more challenging. It is important to consider the shading location and length along the second half of the journey when the thermal sensation has increased, and pedestrian's comfort should be taken handled carefully. Therefore, it is preferable to allocate shade at the last part of the journey as shown in Figure 105. Of course, this depends on the distance travelled, yet, these diagrams created just

intends to clarify the notion. location of the more effective shade in case one recovery point is being applied along the whole journey.

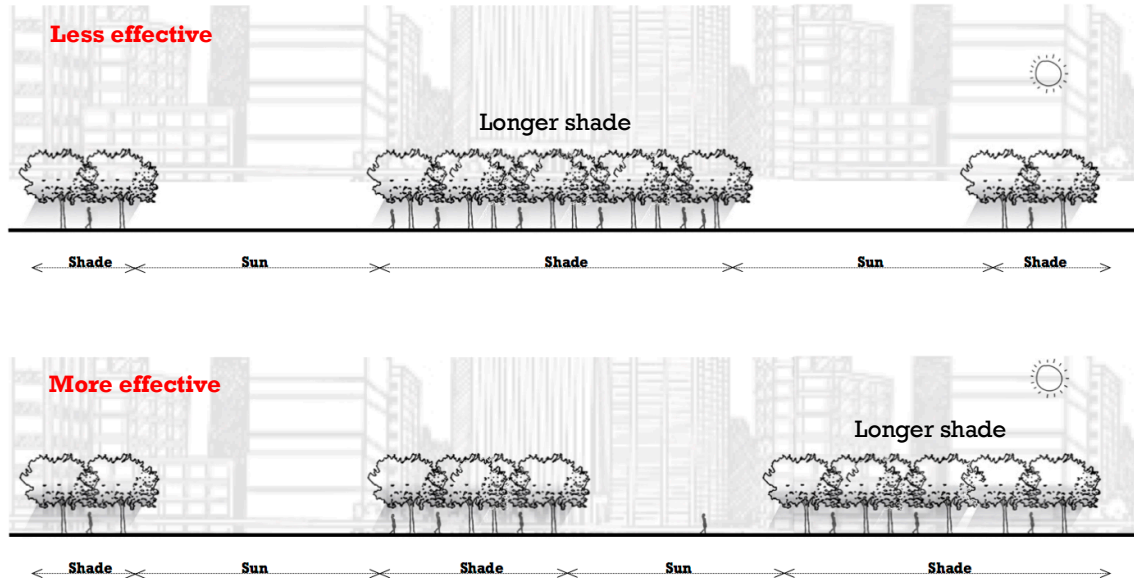


Figure 105 Sketch highlighting the importance of allocating the longer shaded strip along the end of the journey specially when the distances travelled increases.

7.3.3. Length

Urban planners look for solid numbers when designing an urban master plan, to enable them to distribute facilities without diminishing walkability. As presented in this research, climatic factors have a strong influence in cities with challenging conditions. Therefore, a simple hypothetical formula is presented to roughly predict the actual distance that recovery conditions could extend.

If: $D = C$

where D is the distance between facilities, from A (start of the journey) to B (end of the journey) and C is the distance that pedestrians can walk comfortably at different times of the year.

And if: $C = X^{\text{period}} + Y^{\text{period}}$

where X^{period} is the tolerable distance for pedestrians at each climatic period

and Y^{period} is the added distance for pedestrians at each climatic period after recovery

Therefore: $Y^{\text{period}} = C - X^{\text{period}}$

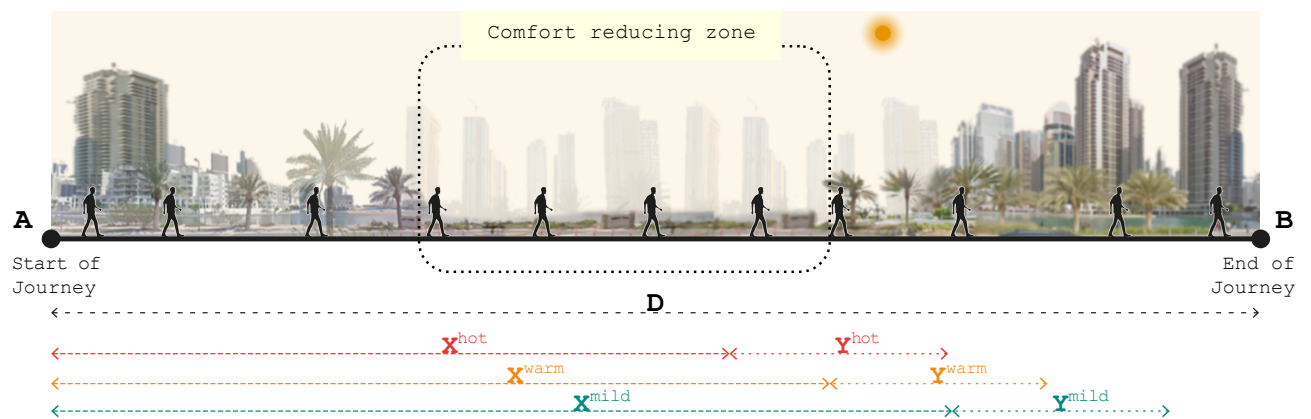


Figure 106 Schematic diagram showing how to identify the location of the recovery conditions, which should follow the comfort declining zone.

It is worth noting that multiple aspects influence the value of Y^{period} , which is specified by the effectiveness of the recovery. The effectiveness of the recovery is specified by its frequency and location (described above), depending on the location, length and frequency of the comfort reducing zones in the journey.

7.3.4. Physical form

Wind and shade are the two fundamentals envisioned to improve the microclimate of outdoor spaces. Therefore, it is important to form a structure that provides shade without blocking wind flow. This has been investigated through long-term environmental monitoring to measure certain spaces and through microclimatic simulations conducted for the three typical periods.

Findings reveal that the coolest space was always the one that was shaded by a building. This kind of space had no horizontal surfaces obstructing the heat release from any surface, but it still lacks shade at midday. Thus, it was even warmer at this time than other spaces. However, the heat absorbed then was released easily as soon as shade began to cover the space, due to its morphology. This effect did not vary even for spaces with trees.

Wind flow induces convective process on the various surfaces, promoting the release of heat into the space. Where there are no obstructing surfaces It promotes the flushing of a high MRT, which makes spaces cooler and improves thermal comfort. Therefore, in this climate, it is essential to design shading and landscape features that do not obstruct the wind flow.

The shading and ventilation strategies should be selected according to the times when the space is used. The four strategies demonstrated below (Figure 107) allow planners to select the shade and wind screens that are most effective at different times.



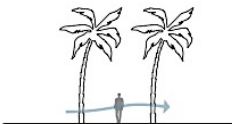





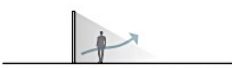

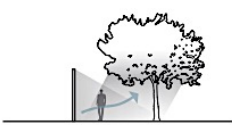

	Wind access	Shade
① Palm tree 		<input type="radio"/> Morning <input type="radio"/> Midday <input type="radio"/> Afternoon
		<input type="radio"/> Morning <input type="radio"/> Midday <input type="radio"/> Afternoon
② Tree 	 *parallel to wind	<input type="radio"/> Morning <input checked="" type="radio"/> Midday <input type="radio"/> Afternoon
	 *parallel to wind	<input type="radio"/> Morning <input checked="" type="radio"/> Midday <input type="radio"/> Afternoon
③ Screen 	 *parallel to wind	<input checked="" type="radio"/> Morning <input type="radio"/> Midday <input checked="" type="radio"/> Afternoon
④ Screen and trees 	 *parallel to wind	<input checked="" type="radio"/> Morning <input checked="" type="radio"/> Midday <input checked="" type="radio"/> Afternoon

Figure 107 Shows the four strategies identified to shade and ventilate the outdoor spaces passively and the level of shade and wind access provided by each.

It should be noted that applying a wind source incorrectly can worsen the air temperature and thermal comfort level in a given space. An example of this is shown below (Figure 108). In the Abu Dhabi international airport, a taxi and bus station has fans under a tensile canopy to increase people's thermal comfort while they wait. The air temperature measured in June at 2:00pm underneath the canopy was 3.4°C warmer than that outside the shade, recording 37.9°C. The relative humidity was 63%, higher by 9% than that outside the shade. The canopy reduced thermal comfort mostly because of the way in which the fans spread the heat. The convective process of the heat flow in air allows hot air to rise. The hot air is due to the high MRT radiated from the different surfaces. This is blown down again by the fans, creating a warmer effect overall than in the surroundings.



Figure 108 A ventilated canopy in the Abu-Dhabi International Airport waiting area. The fans located at the top circulates the hot air rising from the internal surfaces back to the lower level.

In general, urban designers should benefit greatly from the shade provided naturally by buildings. Shading elements should not obstruct the convective exchange underneath, so as to avoid heating up the spaces at other times of day. Wind flow should be improved by orienting the shading elements parallel to it. Moreover, in an urban layout wind channels can be created by adding wind catchers and screens that induce and orient winds to a desired location. The paths of these channels should avoid hot spots, to prevent heat from spreading through an urban layout. Therefore, the wind and shade screens should physically represent the form of shade and wind required.

7.3.5. Materiality

The literature and fieldwork discussed previously consistently extol the importance of improving the albedo characteristics of all the materials used in hot outdoor environments on both a micro and a macro scale. Materials with high albedo reduce the ability of a space to absorb and retain heat, which contributes to a lower MRT values, thus improving thermal comfort. For pedestrians, the material of the ground usually has most influence due to its extent. Therefore, pedestrians' pathways should be paved with materials that are not prone to overheating, have albedo and a pale colour. Using grass also contributes to lowering the MRT significantly, due to the properties of vegetation. However, in desert climates, such as Dubai, reducing the water consumption remains a challenge. Therefore, the ground material of the recovery spaces should be selected according to regional climatic considerations.

In 2015, Sandra Piesk (Stevens, 2015) introduced the possibilities of using palm leaves in construction in a project that she launched in the UAE. Her project was adopted by the United Nations and named *the food shelter*. The project dealt with creating shading structures from palm leaf stems covered by a tensile fabric. The simple and effective design (Figure 109) demonstrated that blending traditional materials and modern building techniques can deliver rapid, sustainable and cost effective solutions to local needs. The idea relied on free and plentiful materials and can be executed by hand without the need for heavy machinery.

The palm leaf stems, from a natural and local source is not only sustainable, but also strongly resists overheating. Thus, waste and extracts from palm trees should be considered for weaving shade and wind screens. The food shelter materiality and design have inspired the wind and shade screens proposed in this study. These screens should be designed contextually, exploiting local materials such as palm leaf stems.



Figure 109 Images of the food shelter structure created from the palm trees

7.4. Testing physical paradigms using ENVI-met

7.4.1. Aims and objectives



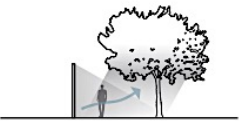
As stressed above, this study does not aim to provide a specific design that embodies recovery factors. Rather, it seeks to offer a methodological concept that will help urban designers and planners create extended routes which provide comfort without the need for continuous shading and/or cooling. Numerous strategies could be developed to improve the microclimate of particular outdoor spaces; however, this remains a function of the urban nature of the place. Therefore, only the strategies revealed through field and analytical work (see Part II) were found most effective in creating the cooling pockets that were tested in ENVI-met.

The aim of running the simulations was to ascertain the ability of the shade and wind screens, representing recovery factors, to create cooling pockets in particular spaces along the daily walking routes. Pedestrians' comfort as they passed through those spaces would be improved significantly, which would encourage them to walk for longer distances and more days of the year. This hypothesis has been validated by thermal walks described in Chapter 5.

7.4.2. Simulation scenarios

Initially, numerous strategies, including all those illustrated in Figure 107, were simulated to reveal the different potentials for improvement. However, due to space and time limitations only three scenarios were selected for demonstration, on the basis of their effectiveness to enhance comfort levels using PET. These scenarios are contingent upon allocating various strategies for screens (Table 6) at certain locations to provide shade and orient wind, and upon improving the albedo characteristics of the ground surface of the spaces. More details of these scenarios are given below and illustrated in Table 6.

Table 6 The three strategies used to develop the simulation scenarios

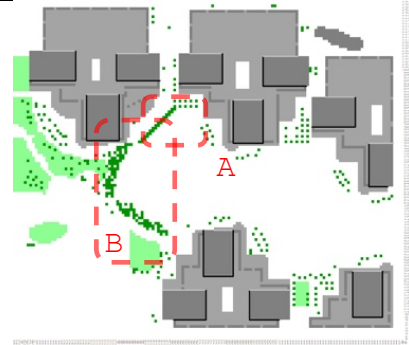
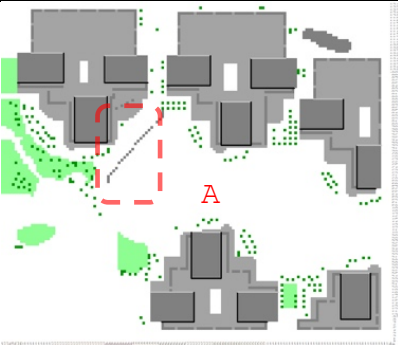
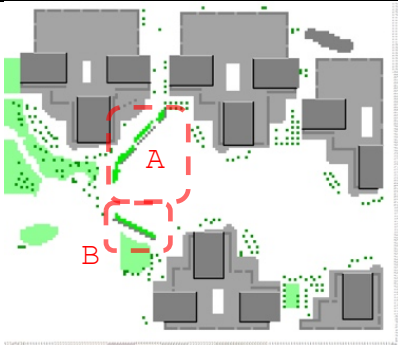
1. Screens of trees	2. Shading screen	3. Screens, trees & albedo
		

Using the software's capacity to create curvilinear or flexible forms, the screens could only be created as staggered walls which had the same default characteristics as the walls of the buildings. The screens were added at a single location (point A) or at two locations (points A and B) (Table 7) to orient the

prevailing northwest wind, accelerated by the two adjacent buildings, along the pedestrians’ path. Each wall has a non-continuous linear form, in reaction to the heavy turbulence and the lower wind speeds that resulted when the continuous walls simulations were first run. These walls were also 5m high, to record the best possible PET values; these were not obtained by the 4m and 8m height scenarios that were tested initially.

The first scenario named *screens of trees* applies a whole screen of trees in place of the wall at both points A and B, due to the weaker ability of trees to orient wind that was revealed during the initial trials. After a few initial trials of tree canopies of different heights (10, 15, 20m), the trees used in this scenario provided a 20m high canopy, since this recorded the lowest PET values. The second scenario, named *shading screen*, uses a wall 5m in height at point A. The third scenario, named *screen, trees and albedo*, combines the previous two strategies into shading screens that incorporate both wall and trees and are applied at both points A and B. The ground material is also modified to pavement tiles with a higher albedo. The screens are based upon the fourth strategy shown in Figure 107, and consist of a linear screen of trees adjacent to the wall.

Table 7 The three scenarios modelled in ENVI-met

<div>1. Screens of trees</div>  <div>Linear trees at A and clustered trees 20m ht. at B</div>	
<div>2. Shading screen</div>  <div>A single wall of 5m ht. at point A</div>	<div>3. Screens, trees and albedo</div>  <div>Two walls 5m ht. and trees 20m ht. at A and B</div>

7.4.3. Initializing the Simulation

Because the warm period is the time when pedestrians start to develop discomfort outdoors, it was the focus of the simulations in the present study. This set all the simulations in the month of April between 5:00 and 18:00. Three times of day were extracted using LEONARDO for analysis, namely, morning at 8:30, midday at 12:30 and late afternoon at 16:30, the times when these routes were being most used. The modelling and input files used the same data, grid scale and grid rotation, which was typical of those used in the previous runs (see section 6.4.3).

7.4.4. Outcomes

Visuals of the four scenarios show the PET values and the wind direction and contours. The outcomes presented below from Figure 110 to Figure 118 are comparisons between the original output files extracted for each scenario and the base case scenario. The base case scenario represents the existing site conditions in April. The base case model is discussed above in section 6.6.2 where the PET values were reviewed from Figure 84 to Figure 86. However, to recapitulate the previous findings, in the average air temperature of the base case scenario, the values were 27.7⁰, 33.7⁰ and 34.7⁰C at 8:30, 12:30 and 16:30 respectively.

Comparative analysis provides a difference value in PET, named by the software the absolute difference. However, the values shown describe the relative differences, since absolute values cannot be negative. Therefore, it may be assumed that the positive (+) and negative (-) signs next to the figures indicate the direction of improvement. When the PET values are negative, they indicate an improvement, meaning that the PET values in the base case scenario were reduced. When the values are positive they indicate a decline in comfort, meaning that the PET values in the base case scenario were increased. Nevertheless, the values are not meant to be assessed precisely in absolute terms. Validation tests were carried out, running two identical models, where PET and Ta output files were compared with the same timing to verify the comparative ability of the software. This revealed that the software provides reliable values for comparative analysis with a precision of 1K. Therefore, when reading the PET values on the visual below (from Figure 110 to Figure 118), the range of readings between -1.0 K and 1.0, were considered insignificant and ignored. Also, the path were pedestrians have been interviewed and the four spaces used for data monitoring were marked on the visuals below.

Screens of trees were applied along the path at points A and B where recovery was required (Figure 112). At 8:30, no changes were observed except underneath the canopy (Space B). Nevertheless, these improvements were significant and reached 15.2K. The reason for such improvement is deemed due to the lack of ventilation in this space as found during the environmental monitoring. At 12:30, the trees remarkably improved the PET, between 4.5 and 1.5K (Figure 111). At 16:30, the improvements extended to 9.6K, specifically along the areas where the trees were positioned (Figure 112). This scenario highlights the effectiveness of trees to improve comfort specially at midday and late afternoon, which agrees with the earlier findings from the environmental monitoring.

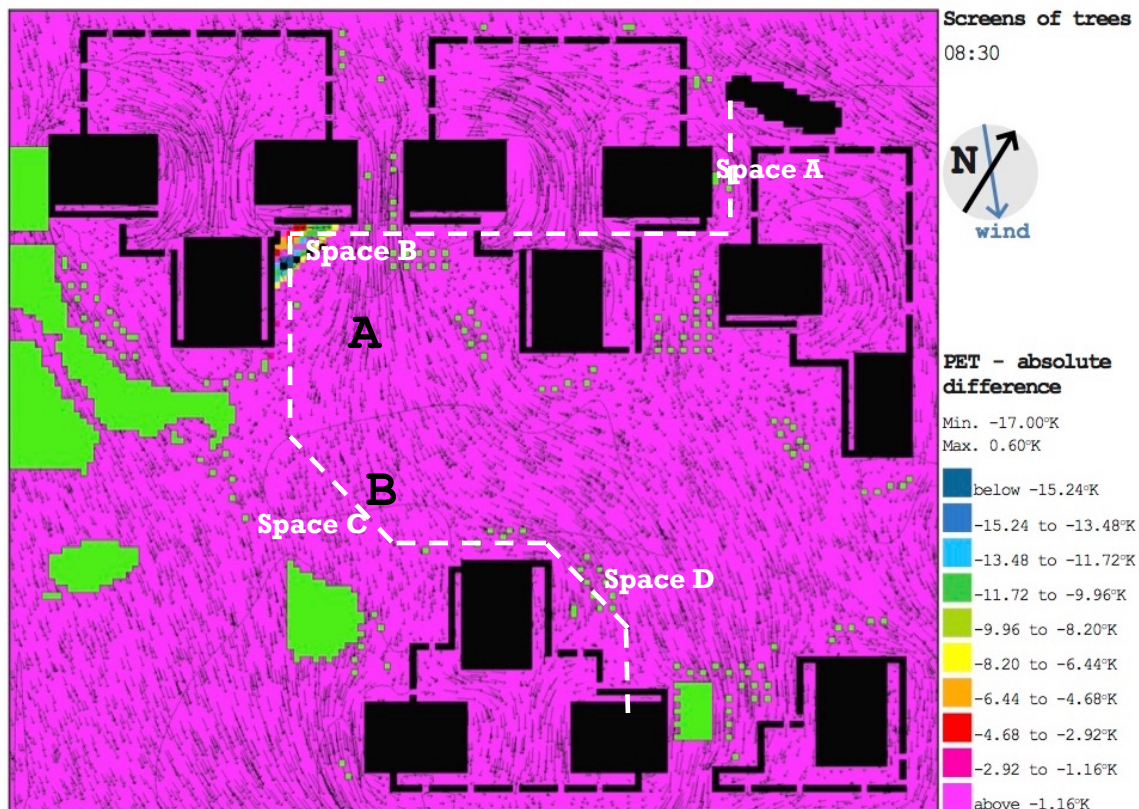


Figure 110 Comparison of PET between the screens of trees and the base case scenarios at 8:30

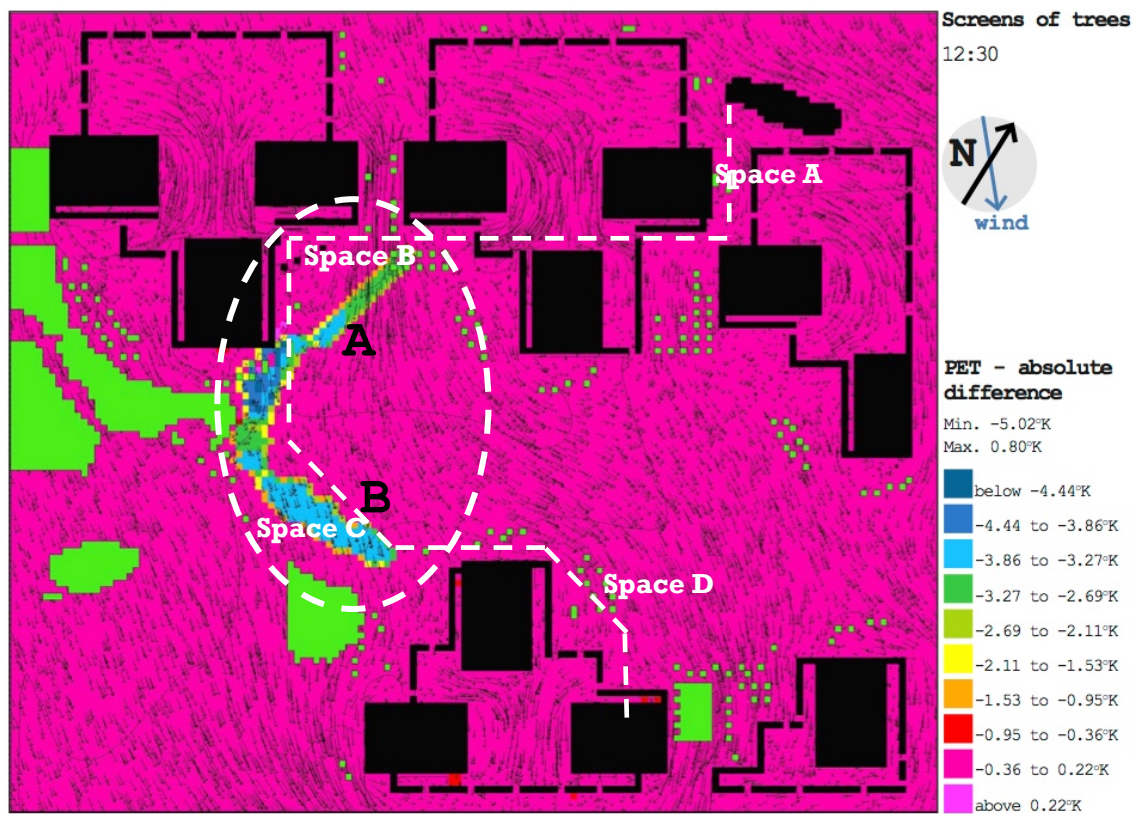


Figure 111 Comparison of PET between the screens of trees and the base case scenarios at 12:30

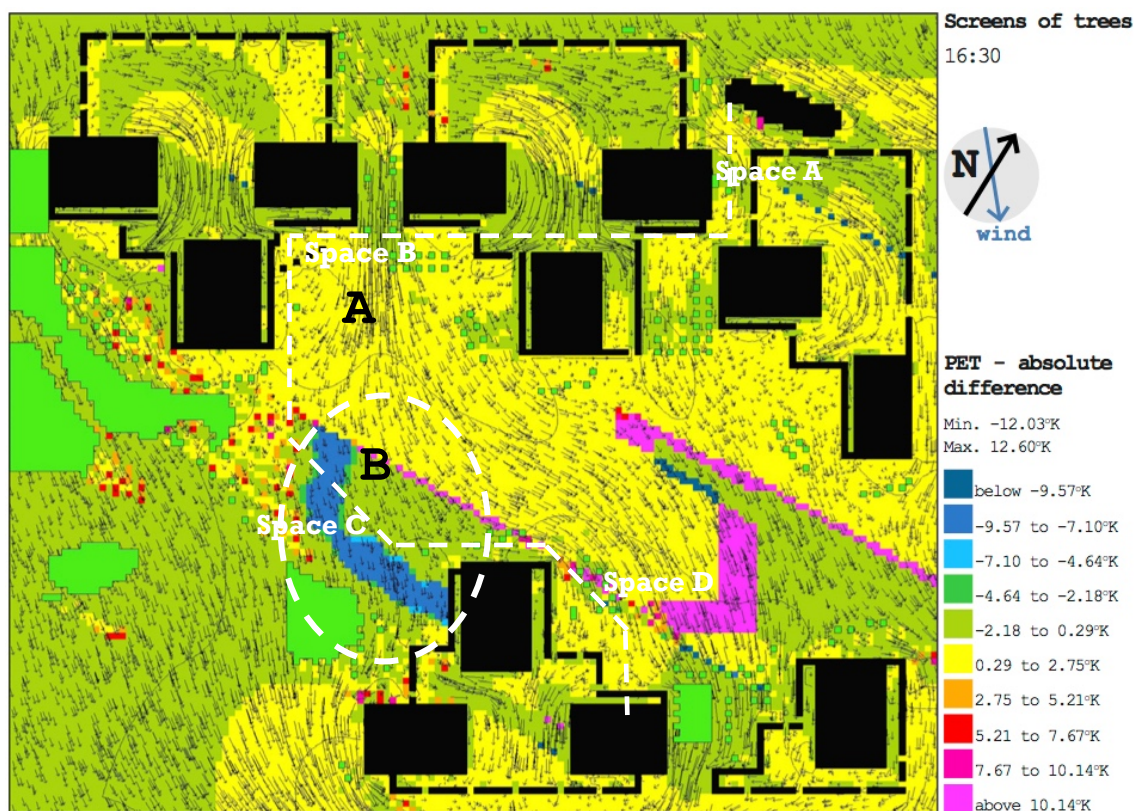


Figure 112 Comparison of PET between the screens of trees and the base case scenarios at 16:30

The influence of the 5m high wall on the PET values was advantageous along one side of the screens, according to the time of day. At 8:00, the presence of the wall reduced PET between 3.1 and 8.5K on the eastern side (Figure 113). This reduction spread noticeably due to the position of the screen facing the wind. However, on the western side of the wall, the PET values improved between 7.6 and 13K. At 12:30, PET declined between 1.3 and 5.6K with a similar extended effect to that in the morning (Figure 114). At 16:30, PET declined by 0.9 to 3.5K. Yet significant improvements were noted at the southern edge of the wall reaching 9.5K (Figure 115). These findings highlight the importance of orientation when designing such screens to ensure comfort improvements and avoid decline. The areas which were influenced negatively by the screens should be positioned away from the wind to minimize their impact on the surrounding spaces.

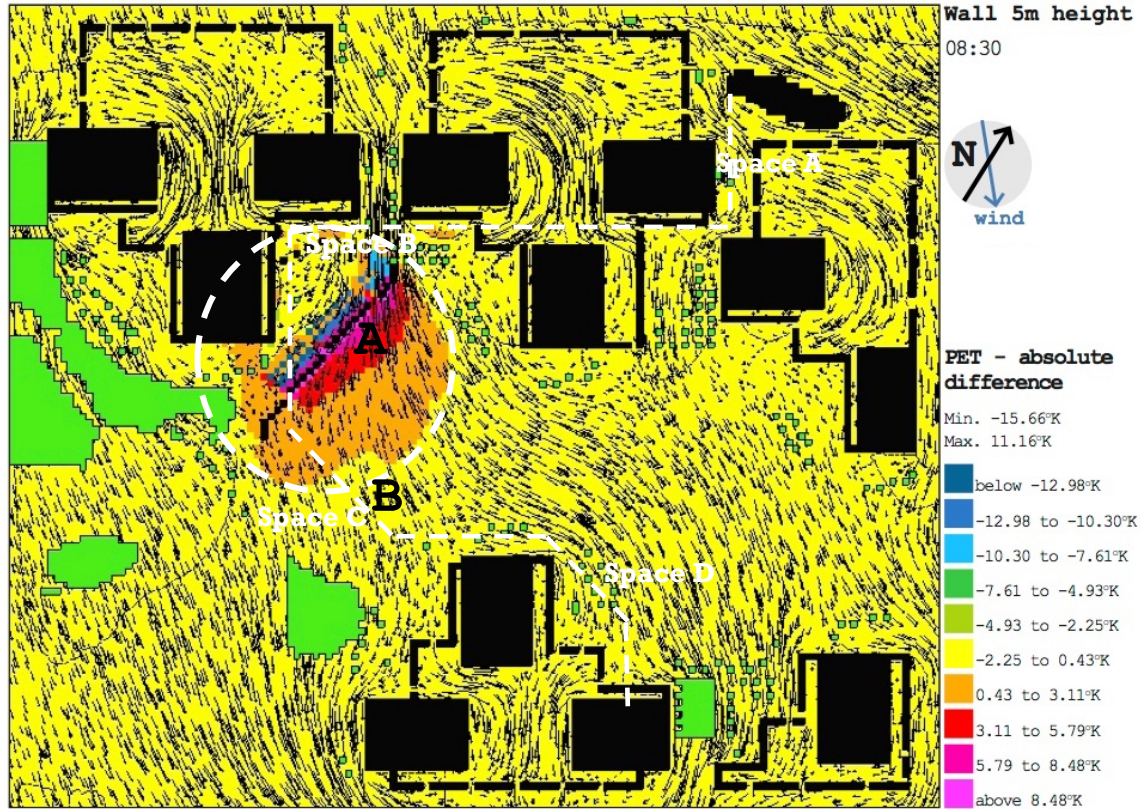


Figure 113 Comparison of PET between the wall of height 5m and the base case scenarios at 8:30

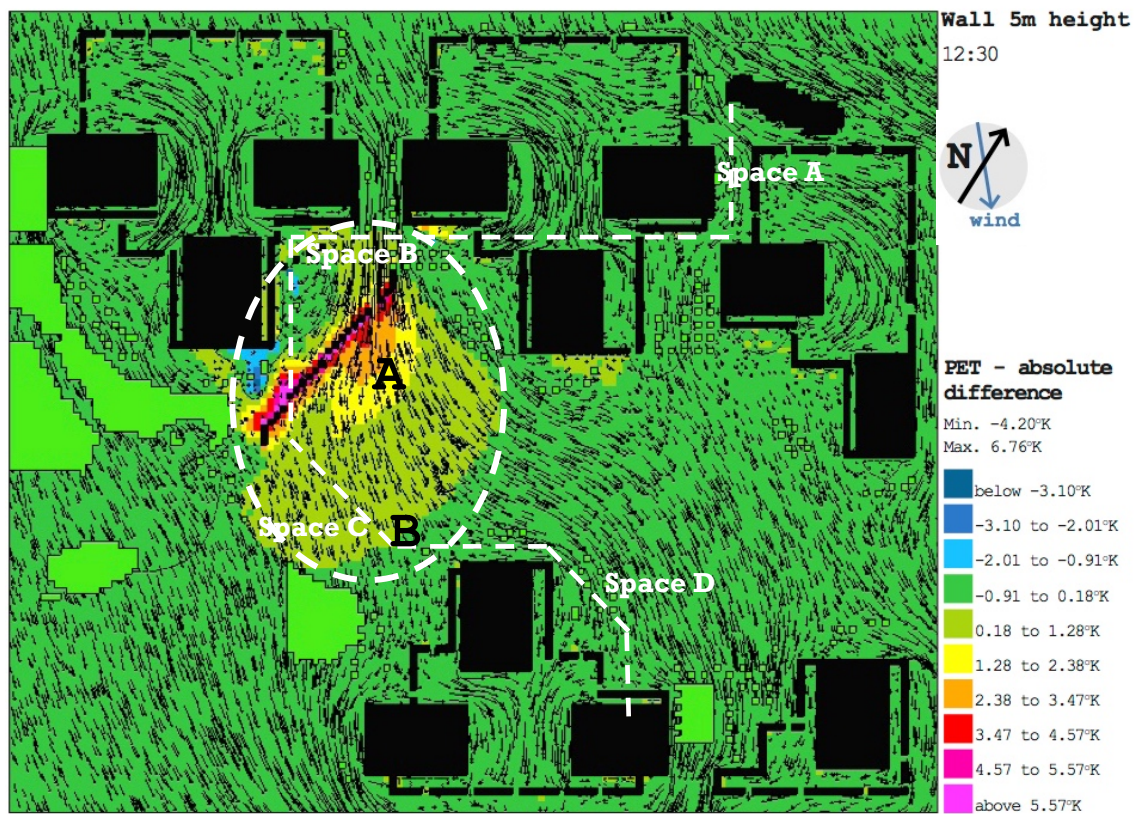


Figure 114 Comparison of PET between the wall of height 5m and the base case scenarios at 12:30

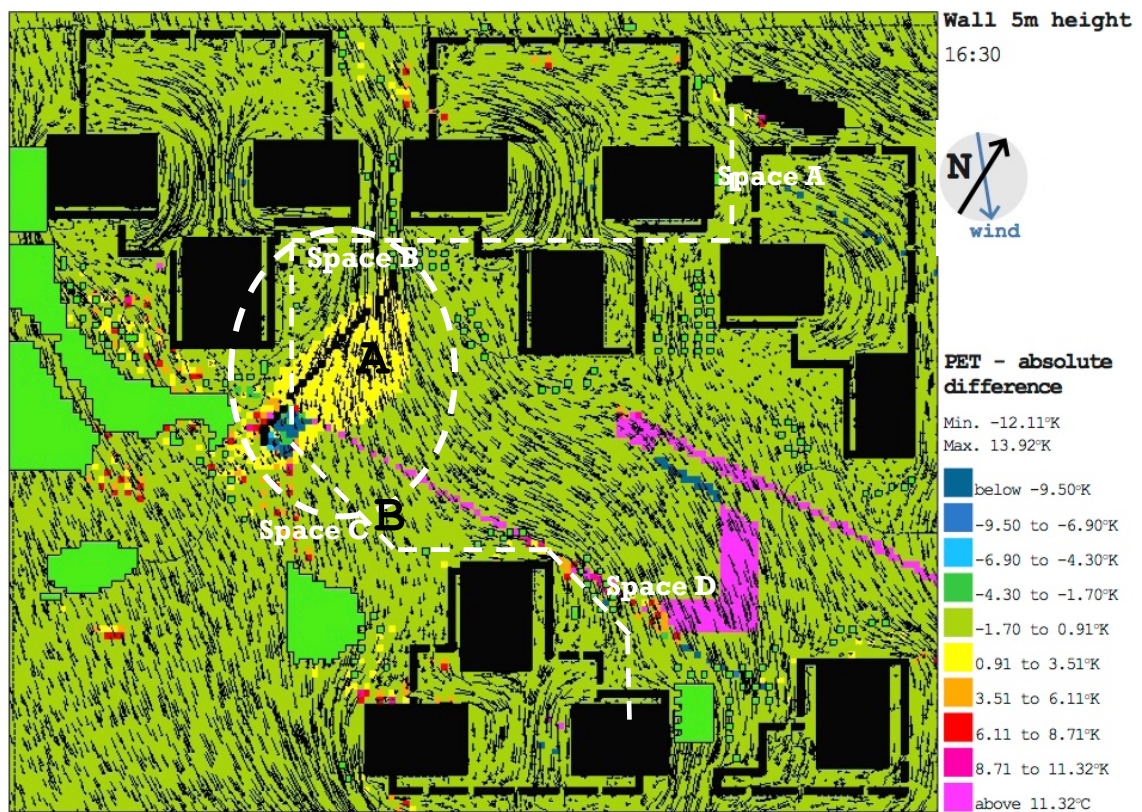


Figure 115 Comparison of PET between the wall of height 5m and the base case scenarios at 16:30

This scenario was formed by combining three variables, the walls, the trees and the improved albedo. Two screens were added at the start and end of the sunny path to increase shade and capture more wind. At 8:00, screen A (Figure 116) had significantly improved PET from the western side by a range of 7.1 to 17.4K. Such an improvement would have allowed pedestrians to recover their comfort levels as they walked along the space. However, at this time of day, the eastern side should be avoided, due to the decline in PET by 3.3 to 10.2K. At 8:00 the impact of screen B was minimal, yet, limited to a 1m area parallel to the screen with a decline in PET by 3.3 to 6.8K. This could be due to the staggered effect of the wall as drawn, which should be disregarded. At 12:30 screen A also improved PET by 5.9 to 7.6K (Figure 117). The screen had the same impact as that in the morning, which reduced the PET from the eastern side by 1 to 6.1K. Therefore, pedestrians should walk along the western side of the top screen but along the northern side of screen B to restore their comfort. At 16:30, improvements in PET from both screens were evident (Figure 118). Screen A improved less, in a range between 0.6 and 3.2K, while those in B ranged from 7 to 9.5K. The findings demonstrate that the way screens are created in this scenario can improve PET values significantly in both locations A and B, so long as they consider the orientation of the path that they should follow.

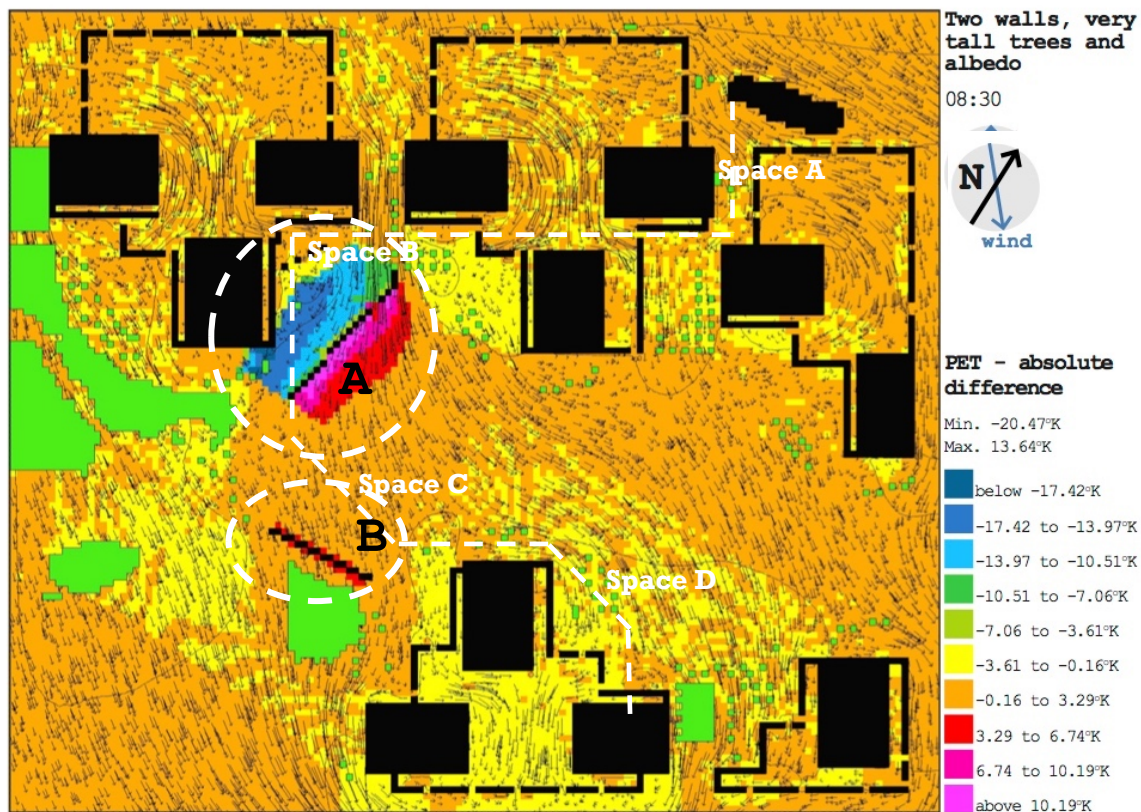


Figure 116 Comparison of PET between the two walls, tall trees and albedo scenario and the base case scenarios at 8:30

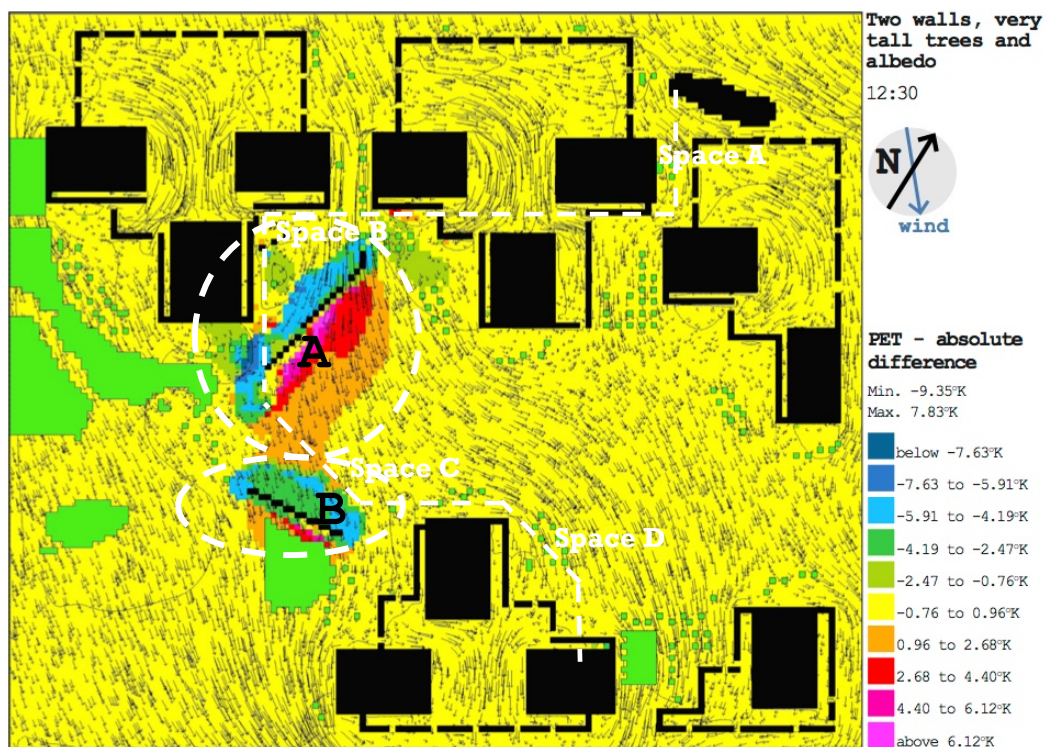


Figure 117 Comparison of PET between the two walls, tall trees and albedo scenario and the base case scenarios at 12:30

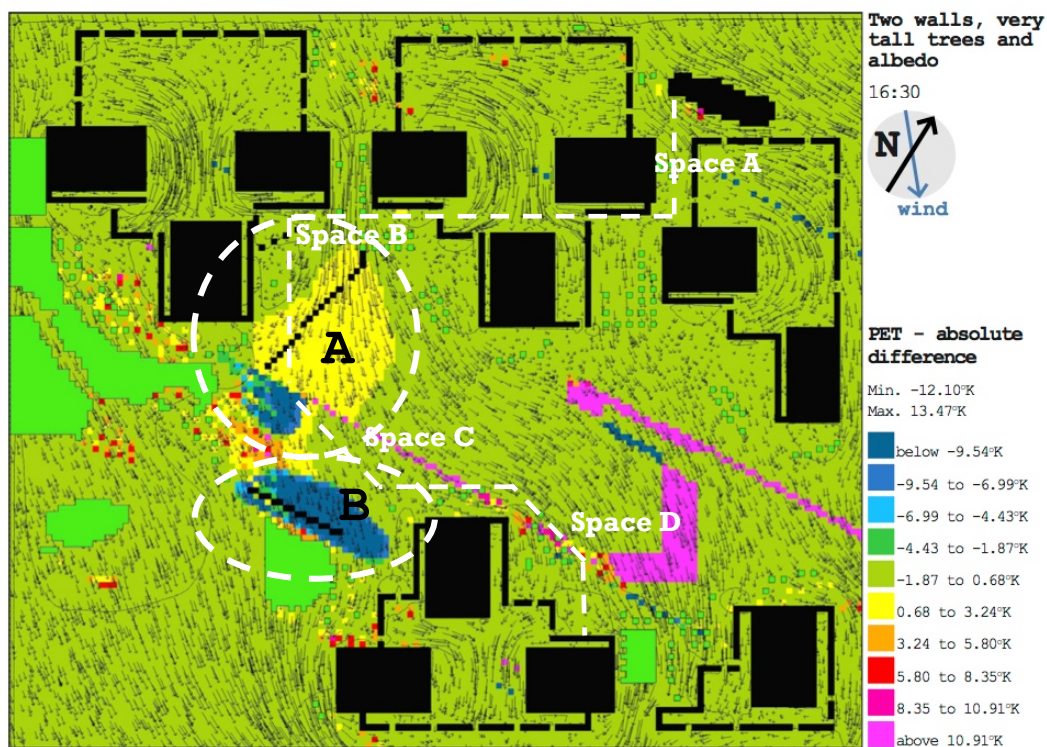


Figure 118 Comparison of PET between the two walls, tall trees and albedo scenario and the base case scenarios at 16:30

7.5. Conclusions

The aim of this chapter was to provide a solution for the lack of walkability due to the microclimatic conditions impaired by current urban design practice. The solution was to apply physical screens that conditioned the microclimate through their efficient ways of shading and influencing wind movement, shading through vertical objects which do not trap heat underneath and providing wind at face level to cool pedestrians. In addition, the use of trees provides shade at midday and the use of grass reduces the MRT.

The method proposed, named *recovery conditions*, offers an instant improvement to pedestrian's thermal comfort as they follow the route and soon reach a cooler thermal sensation. This is mainly due to the improvement in their thermal sensation as a result of face cooling and the improvement in their thermal comfort as a result of heat stress relief as they walk into the shade, coupled with their 'anticipation', which highlights the role of psychological factors in improving thermal comfort. In this way, after walking beside the screens, people will be stay comfortable longer and walk further, depending on the season. The effectiveness of this proposal remains conditional on its placement along the route, its length, frequency, form and material. A visual interpretation of the recovery screens is abstracted below (see Figure 119).

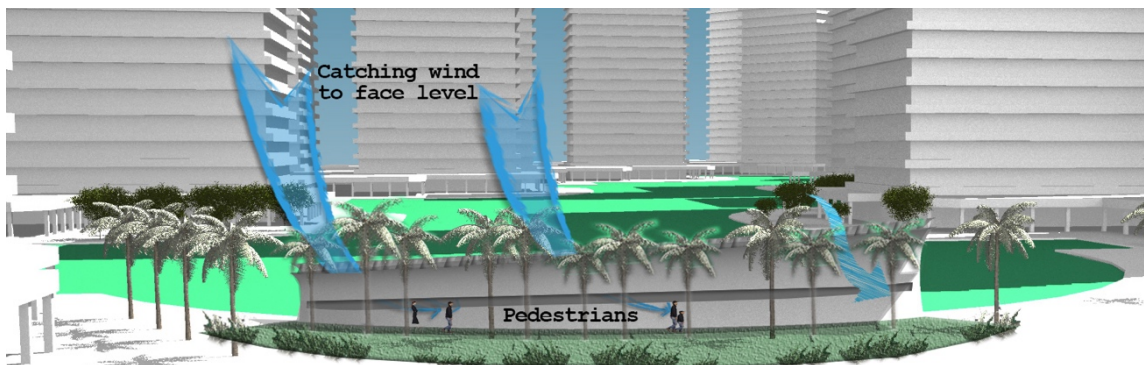


Figure 119 An imaginary scene of the recovery screens added to the comfort reducing zone in JLT, showing pedestrians walking in the afternoon, along the shaded area with the wind oriented to be felt at face level through an opening along the wall.

The lack of comfort indices and tools that consider the changes in the thermal conditions of the sequential spaces requires multiple methods had to be combined. Therefore, ENVI-met was used to reveal the comfort improvements brought by the recovery screens using PET. However, combining this result with the findings from the thermal walks presented in Chapter 5 validates the hypothesis that improving thermal comfort along the recovery spaces allows pedestrians to walk further, depending on the climatic period.

CONCLUSION

Encouraging walkability in Dubai

This study was undertaken in an effort to find critical justification for the short span of walkability in urban communities in Dubai. It aimed to provide one or more solutions that would extend the period that pedestrians were prepared to venture outdoors. It was postulated that improving pedestrians' thermal comfort on their daily journeys would encourage them to walk for longer distances and over longer periods of the year. The purpose of this was to encourage the inhabitants to depend less on cars, improve their quality of life and their satisfaction with their surroundings. These goals were set by the ruler of Dubai, His Highness Sheikh Mohammed bin Rashid Al Maktoum, as a governmental strategy for securing the future happiness and positive outlook of its inhabitants.

An extensive process of fieldwork and analysis was employed to investigate pedestrians' thermal comfort and improve the microclimatic conditions made worse along their routes without the need for massive interventions such as continuous shade or mechanical cooling. These have often been put in place as the only ways of offering comfort. However, the present thesis proposed that sequential spaces between facilities should be assessed jointly in order to create recovery spaces and minimise the areas that provoke discomfort. Such intervention would restore people's thermal sensation and thermal comfort as they walked across these spaces, which would encourage them to walk more.

The study is presented in three parts. Part I, presents the theoretical work reviewed, which relates to outdoor thermal comfort. It focuses on the parameters that influence pedestrians' behaviours in outdoor spaces. Part II reviews the methods of fieldwork and analysis that were followed. Interviews and thermal walks were used to investigate the comfort limits, walking distances and the influence of environmental transitions. Microclimatic measurements were correlated with microclimatic analysis that used ENVI-met, to identify the impact of the spatial attributes of urban spaces on the outdoor parameters. Part III combines the key findings into a single methodological concept, which was tested to verify its applicability. The research adds distinctive knowledge for the urban designers and planners in this region about the impact of the built environment on pedestrians' preferences, comfort limits and behaviours, all of which influence their decision to walk.

Contribution to knowledge

Few investigations have been made on outdoor thermal comfort in hot and humid climates in general, including those of the U.A.E. and its surrounding countries. The current study contributes to filling the gap in knowledge through the information gathered, the analysis conducted and the correlation of the various findings. The knowledge provided forms a solid understanding of the climatic factors that impair walkability, which helps researchers and urban practitioners to design urban areas that encourage this attribute.

Findings from the fieldwork and analytical work conducted during the four years of study were used to produce four academic papers, presented at different international conferences. Most recently (July 2017), a paper was published in Edinburgh's PLEA17, entitled: 'The impact of the microclimatic conditions on pedestrians' comfort'. Another paper entitled: 'Improving pedestrians' thermal sensation in Dubai', was published in 2016 in Los Angeles' PLEA16. The Eco World Summit 2015 held in Abu Dhabi published 'Urban design and thermal comfort: cooling for pedestrians in Dubai'. The CIB-MENA 2014 international conference held in Abu Dhabi published 'Urban design and thermal comfort: shading for pedestrians in Dubai'. The constructive feedback and arguments put forward by international and local participants were very useful in guiding and developing this research.

Summary of key findings

Detailed findings and outcomes are summarized in each chapter. However, fundamental conclusions were derived to answer the research questions identified earlier in the introduction section. Interestingly, some of the answers below show the interconnectedness between the questions raised and the correlation between the methods used.

*Q1. How do the different **spatial attributes influence the microclimatic** conditions and how do they **affect pedestrians' comfort** levels throughout the year?*

A1.1. Influence of the spatial attributes on the microclimate

Long-term environmental monitoring was conducted to observe the influence of the spatial attribute of four outdoor spaces on the microclimatic parameters, which is presented in Chapter 6. Spaces with different characteristics were selected mainly to examine the cooling potential of shade provided from trees, canopies or buildings, compared to the lack of shade. The findings favoured the space shaded by buildings, because they have few horizontal surfaces that obstruct the release of heat. However, such spaces should not be designed for use at midday due to the lack of shade; at this point, space shaded by trees is the coolest.

One of the main findings revealed was the importance of the space orientation in promoting ventilation. Spaces that are continuously shaded during the day may still exacerbate the thermal conditions in stagnant areas; consider the state of the space that was shaded by a canopy. Therefore, in an urban area wind penetration should also be encouraged on a larger scale and this was uncovered by the ENVI-met simulations. This microclimatic analysis tool revealed that wind penetration is extremely favourable in this climate, but warm breezes, blowing air that has been heated by passing through hot spots – should be avoided. Findings from the analytical tool ENVI-met were correlated with environmental monitoring. This showed the value of the tool for assessing urban areas during the

design phase. The long-term field measurements showed that the behaviour of the outdoor parameters does not follow a consistent pattern throughout the year. The warm period, with non-extreme conditions, is the time of year with the highest potential for microclimatic improvements through both shade and wind.

A1.2. Influence of the microclimate on pedestrian's thermal comfort

This was assessed using the method of field interviews (see Chapter 4). The fieldwork involved questioning pedestrians along their daily routes in multiple spaces and at different times of the day and year. This method evaluated the influence of different microclimatic conditions on pedestrians and was used to set out their comfort limits. Clear behaviours among pedestrians were discovered, such as their satisfaction with shade when they encountered it. Their low expectations for their thermal comfort levels outdoors had extended their tolerance to heat. However, their dependence on air-conditioning indoors had made them impatient to venture outdoors when the temperature moderated a little. These findings ascertained the influence of psychological factors on thermal comfort.

*Q2. What are the **limits of thermal comfort** (tolerable conditions) for pedestrians in Dubai? And does the presence of **wind extend such limits**?*

A2.1. Thermal comfort limits

The comfort limits were evaluated through field interviews along pedestrians' daily journeys and were compared to the index mPET to calibrate its use in this environment (see Chapter 4). The limits revealed a comfort range between 18° and 30°C, slightly above that predicted by mPET which was between 23° and 37°C. The comfort range considered the range of thermal sensation: slightly cool and neutral to slightly warm.

A2.2. Wind to extend thermal comfort

The influence of wind on pedestrians' thermal sensation and comfort was tested during the thermal walks presented in Chapter 5. After walking through a non-shaded space for 15 minutes, each of the subjects who participated in the experiment was exposed to an induced wind at 3.2m/s. Wind was found to cool pedestrians' thermal sensation to varying degrees at different times of the year. However, it was effective only when oriented to exposed parts of the body such as the face and arms. Wind speeds below 1.2m/s seemed to have little effect on comfort at different periods of the year and therefore, alignment to the direction of the wind should be considered.

Inducing wind speeds contributed to improved comfort levels, when assessed using the PET index extracted from ENVI-met. The simulated urban area showed an increased wind velocity after passing through the narrow space between two buildings, which had a spreading effect on the microclimatic conditions of the consecutive spaces. Hence, using computational fluid dynamics simulations during the urban design could provide cooler spaces and improve thermal comfort.

*Q3. Can the Physiological Equivalent Temperature (PET) **universal index be used to predict thermal comfort in outdoor spaces in this climate?***

A3. The universal index PET and mPET

The comfort limits discussed in the previous research question highlighted the fact that the index mPET can be used in this climate to predict comfort. However, it is important to consider the differences between static and dynamic conditions when predicting thermal comfort. PET and mPET are both static indices, which showed a steady increase when compared to the pedestrians' votes gathered during field interviews in Chapter 4. This was due to the higher metabolic rates of people when in motion. The lack of dynamic comfort indices obliges designers to use various methods, tools and indices to identify comfort ranges that are suitable for the climatic conditions they need.

*Q4. How do **thermal transitions** along pedestrians' journeys (air-conditioned, sunny and shaded spaces) **influence their thermal sensation and overall thermal comfort?** Does **reducing the thermal distance** between indoors and outdoors that is endured at the start of the journey, extend the distances that pedestrians are willing to travel?*

A4.1. Influence of thermal transitions on thermal sensation and thermal comfort

The thermal walks that were conducted and reviewed in Chapter 5 examined multiple thermal transitions. The influence of the sequential transitions that an individual makes on the thermal sensation and comfort levels is inevitable and should not be evaluated through static comfort indices. The rate of these transitions and the temperature distance between two spaces are the most influential parameters and should be designed sensibly to avoid discomfort. Transitional spaces that act as medians should be added at high successive changes or wide temperature gaps between the spaces.

A4.2. Influence of the thermal distance

The wide temperature gap between the air-conditioned indoor spaces and outdoor ones is one of the main concerns in Dubai, where it can exceed 20°C. The thermal shock endured at building exits proved to deter many people from walking at many times of year. Placing shaded spaces at building exits reduced the temperature distance and reduced the instantaneous rise in pedestrians' thermal

sensation. Therefore, applying transitional spaces between indoor and outdoor spaces is essential, particularly along utilitarian routes.

*Q5. Are outdoor conditioning measures of **solar control and wind movement enough** to improve pedestrians' thermal comfort?*

A5. Influence of shade and wind on improving comfort

The environmental monitoring, interviews, thermal walks and the ENVI-met simulations ascertained the ability of shade and wind to improve pedestrians' thermal comfort in this climate. The influence of shade and wind has a direct and an indirect relation with thermal comfort. Under their direct influence, people perceived shaded spaces as cooler, which improved their comfort. Indirectly, shade reduced the Ta and MRT, which cooled the microclimate and accordingly improved comfort. In addition, wind reduced RH and promoted skin cooling which enhanced people's thermal sensation and comfort. However, the attributes of outdoor spaces should be designed sensibly to provide efficacious shade and wind. Shade should be designed in accordance with the time that the space is used. The different forms of shade investigated, such as trees, canopies, buildings, etc. were found to provide conditioning at different times of the day and year. Therefore, to encourage more people to walk daily, the methods to increase shade along their routes should serve the time when the spaces are most fully occupied. This research proposed the need to provide recovery conditions based upon shading screens that orient the wind.

*Q6. How long do pedestrians **tolerate lack of shade**?*

A6. Pedestrians' tolerable conditions

The limits of tolerable conditions were examined when there was least shade using the method named thermal walks, reviewed in Chapter 5. Conditions were tolerable for a maximum of 10 minutes during the warm and mild periods and 8 minutes during the hot period. Also, the time of exposure can help urban planners to locate restorative facilities. This finding could be used to assess the efficient location of the city's metro stations if a walkability radius were applied. However, the information provided requires further investigations of the types of facility in relation to the urban areas.

Research limitations and challenges

The multiple methods designated to cover the gaps of knowledge that were determined earlier have been very challenging, on several levels. These methods relied in large part on on-site observation, interviews with pedestrians, experiments with fixed subjects and data logging measurements, which were taken by the researcher. An extensive effort was made to overcome the limitations of financial and human resources without compromising the flow and credibility of the process. It was essential for the scope of the investigation to consider all three climatic periods and therefore the fieldwork had to extend over a year.

The lack of dynamic indices to predict pedestrians comfort necessitated the use of a static index and ENVI-met to test the proposed intervention. The information gathered and the analysis of both urban areas that were chosen for the case study revealed common issues, but it is still uncertain whether these findings can be generalised to all urban districts in the city. Dubai has a diverse urban public realm in many areas, which requires critical evaluations of the applicability of the present findings. To heighten the generalisability of the findings on the urban experience, more urban spaces should be evaluated, and more interviews should be conducted that follow the methodological approach adopted in this study.

Given the limitations of the resources, it is believed that the number of open spaces, number of subjects used, and the instruments selected for exploration present a satisfactory balance between the feasibility and generality of the outcomes.

Recommendation for future research and practice

This study can benefit researchers and urban practitioners in Dubai and cities with similar climatic conditions. The material presented enables researchers to develop the knowledge provided in many directions. A few suggestions may be found below.

- From the thermal walks presented, the basis for a dynamic index could be established to predict pedestrians' thermal comfort based on the fluctuations in thermal transitions. Former methods that were established, but not developed, such as BOT-WORLD and PEDNATAS, could also be advanced when incorporating the findings presented.
- This research may encourage researchers who are concerned with thermal transitions to develop a sequence of thermal conditions that would optimise an individual's comfort. This could involve more thermal walks, this time focusing on the relationship to the antecedent space. A sequence of three spaces or more could supply much knowledge that is yet missing.

- The influence of different forms of transitional space at building exits and their influence on people's thermal sensation is a vital thread of research in the U.A.E. and the Gulf region. Developing actual standards for such spaces would be a welcome addition to knowledge.
- The notion of recovery could be developed further, by deriving empirical formulas to help calculate the length of time needed and its optimal position along a route.
- Design materials and forms could be investigated to embody the properties of the recovery spaces in physical paradigms. The functionality of these designs could be tested further through actual structures on site.
- Testing the influence of the recovery conditions in the three climatic periods using the criteria that were applied in this study would reveal their effectiveness throughout the year.
- The TSV and TCV gathered during the interviews could be used to establish the first thermal comfort index for the U.A.E. The data could also be used to calibrate other indices than that used in this study (PET and mPET).
- The influence of multiple factors on walkability, such as car ownership, the purpose of walking, background, etc., could be investigated further, using data from the interviews.
- Further research could investigate the trees and vegetation with good drought tolerance that are most suitable. Since palm trees need little water but provide poor shade cover, design configurations to fill the gaps between the branches could be made to improve their efficiency in regions where water is scarce.

This research could also be useful to urban practitioners in Dubai and the U.A.E. in designing for both new and existing urban communities. Importance should be given to the concerns raised during field observations, to enable more conducive spaces to be designed. Some recommendations are given below.

- This research clarifies the impact of the problematic spaces named as comfort reducing zones, defined in Chapter 7, which has a significant influence on the walkability patterns in urban areas. There is a need to critically identify these zones during the early design process and avoid them in a master plan. They not only affect people's existence outdoors, but also burden the thermal environment with excess heat.
- Architects and urban planners should select the materiality of outdoor spaces to eliminate those with low albedo properties from the region.

- In Dubai, landscape and trees should not serve aesthetic purposes only; instead, they should serve the use of outdoor spaces, providing more shade and improving the thermal environment. Placing the same number of trees in a line or a clump to provide a continuously shaded area has a better influence on pedestrians' thermal sensation.
- The air temperature levels of mechanically cooled building exits and lobbies should be more responsive to the outside temperatures and accommodate seasonal changes. This would reduce the thermal shock endured when moving between indoor and outdoor spaces, which probably affects people's health and satisfaction with the conditions outdoors.

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APPENDIX A: Questionnaire for Field Interviews in JLT And Greens

Date		Space #		Air Temp		Wind Speed		
Time		Survey #		Rel. Hum		Globe Temp		

1. Gender

1. Male 2. Female

2. Age range

1. <19 2. 20-44 3. 45-64 4. >65

3. Clothing

1. Shorts/ skirt + Sleeveless	4. Pants/ skirt + Sleeveless	7. Pants/ skirt + Jacket
2. Shorts/ skirt + Half sleeve	5. Pants/ skirt + Half sleeve	8. Abaya/Veiled
3. Shorts/ skirt + Long sleeve	6. Pants/ skirt + Long sleeve	9. Galabeya

4. How do you feel now?

1. Cold	2. Cool	3. Slightly Cool	4. Neutral	5. Slightly Warm	6. Warm	7. Hot
-3	-2	-1	0	1	2	3

5. How would you describe your overall comfort level?

1. Very Comfortable	2. Comfortable	3. Just Comfortable	4. Just Uncomfortable	5. Uncomfortable	6. Very Uncomfortable
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6. The thing that bothers you most about the weather is

1. Air Temperature	3. Humidity	5. Sun/Solar Radiation
2. No wind	4. Dust	6. Nothing

7. Walking to or from the

1. Mosque	3. Park	5. Metro
2. Market	4. Office	6. School

8. How long have you been walking?

1. 1 - 2 min	3. 6 - 8 min	5. 12 - 14 min
2. 3-5 min	4. 9 - 11 min	6. > 15 min

9. Shading condition of previous space?

1. Full tree shade	4. Little building shade	7. No shade
2. Little tree shade	5. Full canopy shade	8. Indoor AC
3. Full building shade	6. Little canopy shade	9. I don't know

10. How often do you walk along this journey?

1. All year	3. Not when its too hot (June, July, Aug)
2. Often but not regular	4. Rarely

11. How long have you been living in Dubai?

1. 1 month or less	3. 7 - 11 month	5. 3 or 4 years
2. 2 - 6 month	4. 1 or 2 years	6. 5 years or more

12. Where have you been living before?

13. Do you have a car?

1. Yes 2. No

14. How do you find the shade in this space now?

1. Good	2. Poor	3. I don't know
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15. Generally, what measures do you take to make your walk more comfortable (when it's hot)?

1. Umbrella	3. Cold drink/water	5. Sunglasses
2. Hand fan	4. Hat	6. Nothing

16. Shading space condition?

1. Tree shade <small>Similar to Space D</small>	2. Building shade <small>Similar to Space A</small>	3. Canopy shade <small>Similar to Space B</small>	4. No shade <small>Similar to Space C</small>
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APPENDIX B: Data Loggers for Environmental Measurements

The Tinytag Plus 2 data loggers have a high reading resolution and accuracy and are housed in robust, waterproof (IP68 rated) cases that are designed for use in a wide range of outdoor and industrial applications. The units feature a coated RH sensor that has good resistance to moisture and condensation, ensuring measurement reliability. The data is extracted from the loggers through a specific computer software that has been provided by the supplier upon purchase. The data is easily transmitted to excel and used for analysis. The specifications and accuracy information is provided below:

Temperature:

Reading Range -25°C to +85°C (-13°F to +185°F)
Sensor Type 10K NTC Thermistor (external probe)
Response Time 3 mins to 90% FSD in moving air
Reading Resolution 0.01°C or better
Temperature Stability 0.005°C/°C
Change from 25°C

Relative Humidity:

Reading Range 0% to 100% RH
Accuracy $\pm 3.0\%$ RH at 25°C / 77°F
Reading Resolution Better than 0.3% RH
Response Time 40 seconds to 90% FSD
Sensor Type Capacitive (external probe)



Figure B.1: Image of the *Tinytag Plus 2* data logger (TGP-4505) used to measure the globe temperature with a probe and the relative humidity



Figure B.2: Image of the *Tinytag Plus 2* data logger (TGP-4510) used to measure the air temperature

APPENDIX C: Data Loggers for Environmental Measurements

The testo 410-2 handheld anemometer with humidity measures air flow, air temperature, and humidity quickly, easily, and accurately. The compact testo 410-2 air and humidity meter is ideal for fast comfort spot checks and timed averaging calculation. Readings appear instantly on a small screen and are to be recorded manually. The specifications and accuracy information is provided below:

Velocity - Vane anemometer:

Measuring range 0.4 to 20 m/s

Accuracy $\pm (0.2 \text{ m/s} + 2 \% \text{ of mv})$

Resolution 0.1 m/s

Temperature:

Measuring range -10 to +50 °C

Accuracy $\pm 0.5 \text{ °C}$

Resolution 0.1 °C

Measuring rate 0.5 s

Humidity - Capacitive:

Measuring range 0 to 100 %RH

Accuracy $\pm 2.5 \% \text{RH}$ (5 to 95 %RH)

Resolution 0.1 %RH

General technical data:

Dimensions 133 x 46 x 25 mm (incl. protective cap)

Operating temperature -10 to +50 °C



Figure C.1: Image of the handheld *testo 410-2* vane anemometer with humidity measurement used for spot measurements

APPENDIX D: Pedestrian's Journeys Analysis

